OLUME 51 NUMBER 12 . . . ONE YEAR THREE FIFTY

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GENERAL ELECTRIC Review

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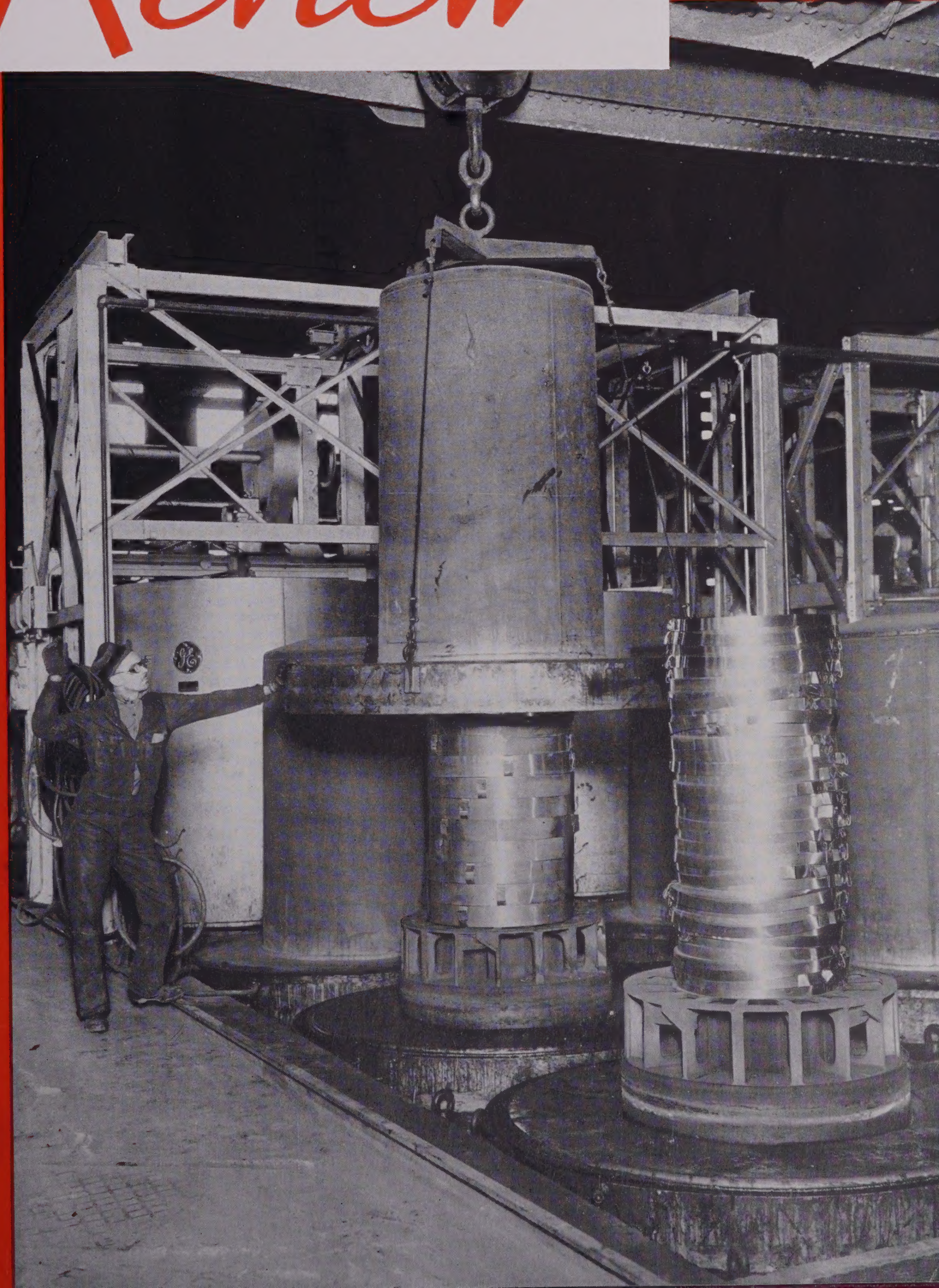

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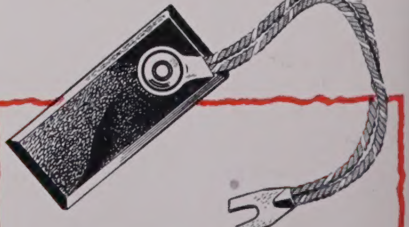

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THE GROWING IMPORTANCE OF STATISTICAL METHODS IN INDUSTRY

By P. L. ALGER

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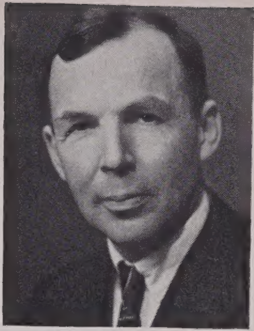

Philip L. Alger

> *Appearances to the mind are of four kinds. Things either are what they appear to be; or they neither are, nor appear to be; or they are, and do not appear to be; or they are not, and yet appear to be. Rightly to aim in all these cases is the wise man's task.*
>
> *Epictetus: Discourses*

A QUIET and unseen, but important, revolution is going on in the basic theories and ways of thinking that guide industrial progress. Until recently, the technical experts in the exact sciences—the engineers, physicists, and chemists—have provided the knowledge that guided industrial developments; while the human side of the program was decided by the nonscientific lawyers and men of business. Now, however, the social scientists—the experts in the humanities—are coming to the fore, and are winning increasing leadership in directing the combinations of men and machines that form industry.

THE NEW LOOK IN INDUSTRIAL LEADERSHIP

A basis for this "New Look" in industrial leadership is the science of statistics, which enables both material processes and human affairs to be defined and predicted with far more assurance than possible in the old days of empiricism. The engineer and scientist of the future must first of all be grounded in statistical methods, since these underlie well-nigh all the technical knowledge on which our future industries will depend, in both the physical sciences and the humanities.

THE INTERRELATIONS OF KNOWLEDGE

As knowledge develops in any field, its expanding theories sooner or later come into contact, and often into conflict, with those in adjoining fields. Many analogies are then brought to light between the methods used in these adjacent areas. Ultimately, a single comprehensive theory is found to apply over a very wide area, and the specialized principles used in each particular field are seen to be corollaries of the underlying fundamental theory.

In this way, electrical, mechanical, thermal, and hydraulic engineering are all tied together by the far-reaching principles of circuit and field theory. Almost all the exact sciences are covered by the solutions of a very few fundamental equations of physics. The Poisson equation, and its free-space version—the Laplace equation; the wave equation, with and without energy dissipation; and the heat equation are of such wide application that the man who is truly familiar with them can well be called a universal engineer.

However, the usual solutions of these equations are all founded on assumptions not exactly realized in practice. For example, "a point charge" or "a unit mass" does not actually begin at an exact point, but instead there is an edge zone of transition in which the charge or the piece of material builds up from nothing to solid substance. Thus, when the dimension of a piece of metal is specified to a few ten-thousandths of an inch, the question arises whether the measurement is to be made to the lowest pit or to the highest ridge on the never-exactly-smooth surface.

The Heisenberg uncertainty principle shows that on a molecular scale the position and velocity of a particle cannot both be exactly known, because the more clearly the particle is observed the greater the energy required in the light beam striking the particle; and the greater this energy the more the particle's velocity is disturbed by it.

In his rapid extension of technical knowledge, the engineer is coming into contact on many fronts with the social sciences. It is still fashionable to draw a sharp line between the empirical sciences, that deal with the behavior of living beings, and the exact sciences, that deal with inanimate objects; but, in fact, the separation is no longer clear. While the engineer has been busy with his (nearly) exact formulas, the biologist and social scientist have been developing rules of their own, founded on the laws of statistics instead of the laws of physics.

For example, opinion polling is now becoming a science, governed by well-developed laws for the phrasing of questions, the choice of "pollees," and the analysis of the replies. The laws of heredity are also well understood, so that new strains of animals and plants with almost any desired characteristics can be developed, given adequate time and money. Insurance actuaries have reduced the predictions of life expectancy, fire losses, and many other risks to a fairly exact science. Such abstruse ideas as those of order statistics, sequential analysis, and the statistical theory of runs have been developed and found highly useful in the analysis and prediction of many sorts of social and biological processes.

This article is so paged that without mutilating other articles, it can be readily removed for filing as a group of full-size consecutive pages.—Editor

During the recent war, for the first time, social scientists and engineers were brought into contact on a large scale, and forced under high pressure to attack problems that neither could solve without the other. A typical example of this activity is that known as "Operations Research," carried on by both British and American groups of scientific personnel assigned to Army and Navy commands in different theaters of operation. These men were charged with the analysis of the over-all performance of men, equipment, and tactics under combat conditions. They included actuaries, biologists, chemists, engineers, mathematicians, physicists, psychologists, and statisticians, thoroughly mixed. Their conclusions led to many improvements in the training of men, the design of equipment, and the tactical employment of both. These were made possible by statistical analysis.(1)

THE IMPORTANCE OF STATISTICAL TRAINING

A statement made by General H. H. Arnold in 1946 before a meeting of the Institute of Aeronautical Sciences gave his views on the great importance of this method of operational research, suggesting that it will apply fully as well to industry in time of peace as to military operations in time of war:

> "Rare was the scientist whose interests led him to consideration of what I may call diffuse problems, connected with operational research. The number of scientists and technologists who applied themselves to the solution of the difficult problems associated with operations was pitifully small. I suspect this failure is a reflection upon our method of training. It seems to me we must do something to encourage greater interest in the application of the method of reasoning to the evaluation of problems which deal not alone with machines, but with the integrated combination of men and machines."

To sum up, anyone conversant with the literature of the social sciences is well aware of the basic importance of statistical methods in this field; and anyone conversant with industrial developments is also well aware of the rapidly growing importance of statistical methods, such as quality control, in industry.

Looking at these two developments together, there is evident a great need for statistical training of our future engineers and business leaders, so that they may be prepared to deal wisely "with the integrated combination of men and machines." Professor S. S. Wilks of Princeton University, has stated this very well:

> "The statistical problems which the future scientist or engineer will encounter will cut across traditional lines. Therefore, in order that he may be properly equipped to deal with these problems, he should have a fairly broad statistical training. The training should cover not only statistical quality-control methods as the term is now understood, but the design of experiments, analysis of variance, and many other topics. It should be built into the training of scientists and engineers, as calculus is now made a part of their basic education."

However, the immediate problem is to put to use the statistical methods that are already of proved value in industry. When the usefulness of these methods is clearly understood, American industry, under the spur of competition, soon will find ways and means to employ them. In so doing, the demand for statistically trained men will grow, and the colleges will rapidly create educational programs to provide the men that are needed.(2)

TEN DIFFERENT WAYS

There are at least ten different ways in which industry can use statistical methods to immediate advantage. Broadly speaking, all these ways depend on the ability of statistics to give a numerical answer, together with an associated numerical degree of certainty, for things that have heretofore been left unmeasured. These ways are in:

(1) Defining the value of observations
(2) Design of experiments
(3) Detection of causes
(4) Production quality control
(5) Getting more out of the inspection dollar
(6) Design specifications
(7) Measurement of human attributes
(8) Operational research
(9) Market research, including opinion polling
(10) Determining trends.

Defining the Value of Observations

The ordinary man, when he sees something happen once, or maybe twice, is prone to accept the event as a fact and to base his further actions upon it. This is especially true if the event falls in line with his prior beliefs. In engineering tests, however, it is the practice to repeat measurements several times, so that not only the average result, but also its degree of accuracy, is determined.

On the basis of only a single "yes" or "no" observation without prior experience, the statistician knows that it is only a nine-to-one chance that between 31 and 95 percent of future trials will come out the same way. Fig. 1 shows the width of the 90-percent "confidence belts" for several sample sizes drawn at random from a large lot. For example, if a sample of ten is found to include three defectives, it is a nine-to-one chance that the lot has between 9 and 61 percent defectives.

The basis of sampling theory may be understood by considering the elementary example of a mixed lot of buttons, of which 90 percent are good and 10 percent are defective. The chance of drawing a good button is 0.9, and of drawing two good buttons successively is

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(1) Numbered references are listed at the end of the article.

$(0.9)^2$, or 0.81. The combined chance of drawing one good and one defective, or of one defective and one good, is $2\,(0.9\times 0.1)=0.18$. And, the chance of drawing two defective buttons is $(0.1)^2=0.01$. Therefore, on the average, 81 percent of all the samples of two drawn will be all good, and only 19 percent will contain defective buttons.

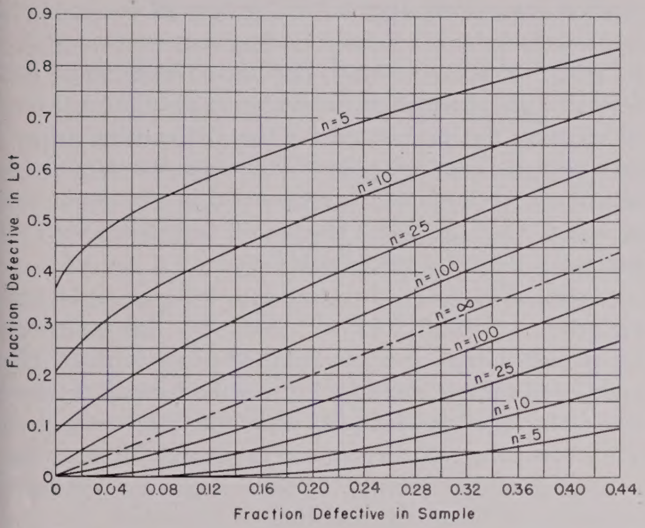

Fig. 1. Boundary curves of the 90 percent confidence belts as applied to checking for defective pieces by the sampling method, using a single sample of *n* pieces drawn from a large lot

That is, 81 percent of the samples drawn will have fewer defectives than the true average of the lot, and only 19 percent will be worse than the average of the lot. This fact, that the average defectives in the lot are more than indicated by the ratio of the unsatisfactory to the satisfactory samples, is a vital point that is overlooked in many specifications.

For example, a specification requiring that only five samples contain no defects would still lead to the acceptance of 41 percent of all lots containing 10 percent defectives.

Throughout industry, day-to-day actions are determined by the results of tests and observations of many sorts. A knowledge of sampling theory is invaluable to those who make these decisions, which must often be based on very limited evidence. Such knowledge enables the experimenter to maintain a stable attitude when faced with erratic trial results, instead of being led astray by hunches.(3)

Design of Experiments

In every industrial process there are many independent variables. To find the best practice, it is needful to choose the best combination of all these variables. The traditional way of doing this is to compare results when one variable is changed at a time, while attempting to hold the others constant. A more modern method is to vary two or three, while fixing some others and letting the remainder vary naturally. Both of these methods require a great many experiments before the influence of each of the variables can be tracked down, especially when they are interrelated.

In the statistical, or Latin square, method, the important variables are changed deliberately in the test program, and all others are "randomized," or left to vary at will. The combinations of variables are so chosen, however, that, by averaging the results with respect to any one variable, the linear effects of the others cancel out. In this way, the needed information can be obtained with fewer tests, in less time, and with greater certainty, than by old methods.

These statistical rules are easy to learn and apply, and they are extremely useful to all concerned with the design of experiments.

For example, if the effects of type of glue, pressure, and temperature on bonding strength are to be compared, the Latin square method suggests that *n* trials* should be made with each of the following combinations:

Glue	I	Pressure	I	Temperature	I
"	"	"	II	"	II
"	"	"	III	"	III
"	II	"	I	"	II
"	"	"	II	"	III
"	"	"	III	"	I
"	III	"	I	"	III
"	"	"	II	"	I
"	"	"	III	"	II

There are then three sets of *n* tests with each glue, each pressure, and each temperature, but no two sets with the same combination. Assuming that all relations are linear, the effects of pressure and temperature are averaged out when the three *n* tests with each glue are summed, the effects of glue and temperature are averaged out when the three *n* tests with each pressure are summed, etc.(4)

Detection of Causes

In any new process, factors are always turning up that change results in an unexpected way. This is especially true when the laws of the process are completely unknown, as in many chemical and biological projects. The problem then is to detect and control these variables before time and money are wasted in wrong directions. The statistician does this by a process called "the analysis of variance."

Having a number of test results and associated values of all the known variables, he calculates the net change in test results when each of the variables was changed, and also the "standard deviation" between successive tests under the same conditions. Comparing these two values of the observed change and the standard deviation, the statistician can see at once whether the observed change is significant, or is only that expected from the laws of chance. In this way, it is possible to extract from a mass of data the influence of any particular variable, and to detect the effects of new or unknown causes.

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*n may be chosen from one to five, depending on the accuracy of the individual measurements and of the process control.

Following this method intensively over two years' time, one laboratory making penicillin reduced the cost of the product to one percent of its original value, while the output and uniformity were greatly improved.⁽⁵⁾

Production Quality Control

The Shewhart control chart applied to repetitive processes in industry provides sensitive indications of production trends, and separates out assignable causes of quality variation, enabling corrective action to be taken before real trouble develops. Also, it enables the effects of small changes in process to be accurately determined, so that improvements can be introduced step by step with full assurance that they will yield the benefits expected.

The usual procedure is to take two to five samples from rational subgroups of production at regular intervals, and record on a chart the average measurement of each group, and also the range between the highest and lowest measurements within each group. Knowing the grand average of ten or more successive groups, and their average range, the "control limits" for the average and the range are calculated (by applying factors taken from statistical tables). These limits are usually chosen to represent departures of three times the standard deviation from the average, which will not occur more than three times in a thousand tests, so long as there is no significant change in the process. Whenever any new group measurement shows a point outside the limit lines, it is practically certain that a significant change in process has occurred, making an investigation to correct it worth while.

The basic idea in quality control is to continually sample the *process*, whereas in inspection the *product* is sampled.⁽⁶⁾

Getting More Out of the Inspection Dollar

The coming trend in industry is to eliminate the inspection process as such, or at least 100-percent inspection, and to put in its place the independent procedures of sorting and auditing.

Sorting consists in separating each unit of product into distinct categories, that may be according to the operator, to the machine, or to the lot of material from which they came, and especially according to the time order in which they were produced. Effort is made to have each operator check the quality of his own work in some manner, making quality-sorting a part of the production process.

Then, as the well-sorted pieces come through production, they are audited by the process of removing and examining well-selected samples at regular intervals. By carefully measuring the samples, and computing the range, the standard deviation, or other statistical quantities for each small lot, accurate conclusions are drawn with regard to the production quality, its trend, and the necessary action to improve it, if need be.

Whether sorting is or is not done, the basic idea in the auditing procedure is to carefully measure a few pieces, instead of to casually inspect all the pieces. In one instance that has been reported, 61 lots of incoming material (containing an average of 350 pieces) were given 100-percent inspection, and were also checked by measurements on 50 samples drawn at random from each lot. The 100-percent inspection method discovered only four defective pieces in three separate lots that were not found by the new (sampling) method, but the new method detected more than 500 defective pieces which were present in 39 of the lots and which were not discovered by the 100-percent inspection method. The time taken to measure the 50 samples was about as much as to give normal inspection to 230 pieces, so that far better results were obtained with 30 percent lower total inspection cost.

In many cases where attributes of a material are determined visually rather than by measurement, acceptance sampling plans are used to advantage. The number of samples taken may then be varied inversely when the quality changes, thus reducing inspection costs when the risk warrants. The sequential sampling method developed during the war enables a quite exact economic balance between cost of inspection and the risk of departing from the desired quality level to be maintained.

With a little experience, the new methods enable uncanny judgments to be formed of what has occurred in the production of the sampled lots of material. In many cases, this information has enabled the purchaser, with no knowledge of the details of a vendor's process, to tell the vendor what changes have occurred in his plant, and when, much to his surprise.⁽⁷⁾

Design Specifications

Since no two units of product can ever be exactly alike, design specifications must state clearly what range of tolerance is acceptable. When many parts fit together to make the final product, these parts must be given such separate tolerances that they can be made most economically, and still will surely fit together. Knowing that the chance variations in dimensions caused by independent processes add "at right angles," and not directly, the designer can allow much greater tolerances than at first appears possible. For example, the standard production limits on a train of small gears for clocks may be so wide that if all the gears in the train were at the lower limit the final pair would not even mesh; while if all were at the upper limit the train would lock solidly.

Besides choosing the optimum tolerances, the methods of gaging must be specified on a statistical basis, and different tolerances again must be provided for the master gages which check those used in production. To develop a really good specification, the designer must know the process attributes of the machines, the operators, and the materials, as well as his own design factors and measuring devices, and all must be expressed in statistically correct terms.

Measurement of Human Attributes

The selection, training, and promotion of operators are greatly assisted by statistical methods of defining human performance. For example, an operator may be asked to perform a given task five times in succession, or at different times and under different conditions. The range of variation in his work measured in this way gives a numerical index of his ability to repeat, and, therefore, of his value for many production purposes.

And, this procedure also may be repeated with several different machines, enabling the uniformity of machines, as well as operators, to be compared.

Aptitude tests of many sorts, which are gaining increasing recognition as a means of measuring human attributes, are really sampling tests. We devise a task as nearly like some element of the final achievement as possible, and infer from the performance in a very few tests what may be expected in the long run. Allowance must be made, however, for the differentials in incentives and in working conditions, as well as the differences between the test and the actual work to be done; all of which are subject to large uncertainties.

Statistical laws are, therefore, of great value in ndustrial personnel work.(8)

Operational Research

The most modern and least developed field of statistical analysis is the study of the combined operations of men and machines. It is natural for the customer who buys a new machine to think all the troubles that occur are due to the design. It is equally natural for the designer to think that the customer has sadly misused his darling creation. Actually, most troubles that arise n such cases are due to unforeseen conditions which are the fault of neither the designer nor the customer; they are troubles that can be remedied by some new part, or some change in the method of operation.

It is the special province of the application engineer to first study the job that is to be done by a machine, then to tell the designer what is required, and the customer what is promised, and, finally, to evaluate the performance of the machine in the field. In this last stage, as General Arnold has indicated, there is a great need for the use of statistical analysis to weigh the meaning of observations, to detect and measure the causes of unexpected results, and to define the performance required of each human and physical element n the entire process.

The procedure of putting a new mill into operation has much in common with that of developing a new chemical compound, or of growing a new kind of plant. In each case, the procedure is governed by some initial hypothesis, but is modified from moment to moment, as records of performance, supplemented by keen observations, suggest that changes be made.(9)

Market Research (Including Opinion Polling)

Finding out what people want, or what they think hey want, is really an extension of operational research into a still less exact field. Instead of studying the performance of a machine that has been built, the market researcher looks for places and people that need new devices, and tries to construct from the answers to his questions a picture of what the needed machine should be like. Here again there arise problems of where to look, what questions to ask, who to ask, and how many times the process must be repeated to get a worth-while answer. How worth while the answer is, and how much time and money it will take to get it, are determined by the skill with which the laws of statistics are applied in the process.

For results to be of value, it is necessary to determine not only what the opinion is but also how strongly the opinion is held. For this purpose, the "split question" technique is useful. A question is worded in two different ways, so as to have exactly the same meaning, but employing words with different connotations. The two forms of the question are addressed to equal numbers of (different) people, chosen at random. If the answers are the same to both forms, it shows that the opinion is strongly held. To the degree that the answers differ, there is uncertainty and a likelihood that the opinion will easily be changed by an emotional appeal, or by some new event.(10)

Determining Trends

Whenever a set of data that is plotted forms a "shot-gun" curve, the method of least squares provides an invaluable means of interpreting the data. The curve which is so drawn that the root-mean-square value of the departures of the test points from the curve is a minimum gives the most nearly correct answer, and the standard deviation of the points from the curve is a measure of the reliability of this result.

There are many instances in industry where the general form of the relation between two variables is known; and there are a considerable number of records of past performance from which it is desired to predict the future results. For example, the percentage ratio of drafting, or of tool cost, or some other sort of expense, to the manufacturing cost of a certain product may be known over a series of years. The ratio will vary with the volume of business and other factors which are more or less well known. By applying the least-square method to determine the most probable values of the coefficients for equations of the proper form, formulas can be derived that will give surprisingly accurate predictions, even though the business varies over a very wide range.

For example, Table I gives the relations of certain overhead charges to sales billed for a manufacturing division over the twenty years from 1929 to 1948. Applying the method of least squares to the first twelve years of this period, the relation of the charges E to sales billed S is found to be

$$E = 0.197\sqrt{S} + 0.0087S$$

This formula is based on the assumption that E consists of two elements: one varying in proportion to the square root of the sales; and the other varying in direct relation to the sales. The first term may be thought of as the charge inherent in carrying on the business with a bare minimum of research, new development, and complaint expenses. The second term includes the cost of development, new models, and troubles incident to maintaining position in a rapidly changing and highly competitive field.

It will be observed from the dotted curve in FIG. 2 that the predictions made with the twelve-year (1929–1940) formula fairly represent the trend of the succeeding eight years. The fact that the actual charges fall below the predictions in the war years is evidence of the curtailed development and large quantity orders for that period. The strike period in 1946, and the reduced orders with high expense associated with reconversion, are evidenced by the excess of the actual charges over predictions in the last three years.

TABLE I

Year	Sales S	Charges E	Predicted Value of E 1929-40 Basis	Predicted Value of E 1929-48 Basis
1929	22.3	1.04	1.12	1.16
1930	22.8	1.09	1.13	1.18
1931	14.4	0.910	0.87	0.90
1932	7.3	0.567	0.61	0.61
1933	5.8	0.502	0.54	0.54
1934	7.4	0.645	0.62	0.62
1935	10.5	0.700	0.73	0.75
1936	15.0	0.844	0.89	0.92
1937	20.2	1.10	1.06	1.10
1938	15.0	0.950	0.89	0.92
1939	16.2	1.04	0.92	0.96
1940	24.4	1.24	1.19	1.23
1941	41.9	1.75	1.64	1.71
1942	71.0	2.11	2.28	2.42
1943	94.0	2.27	2.72	2.91
1944	96.2	2.33	2.76	2.96
1945	88.5	2.48	2.62	2.80
1946	37.1	2.40	1.52	1.60
1947	65.5	2.84	2.18	2.30
1948	84.1	3.12	2.54	2.71

When all twenty years are taken into account (as represented by the full curve in FIG. 2), the method of least squares gives the revised formula

$$E=0.196\sqrt{S}+0.0108S$$

which differs by only six percent from that of the earlier curve. That is, the prediction made in 1940 of the 1948 charges for a given volume of sales comes within six percent of that derived from all the later experience.

There are many hidden relationships between sales volume of a given product and economic data published by the U.S. Department of Commerce, and by Trade Associations. By using the analysis of variance to bring out these relations, and applying the method of least squares to some of them, a wide field for more intelligent long-range economic planning is opened up.⁽¹¹⁾

It Is Just a Matter of Sampling

Perhaps this whole subject of statistical methods may be summed up by the remark that everything comes down to a question of sampling theory. Each day is a sample of life, just as each apple is a sample of the crop from a certain tree, and each operator is a sample of a certain class of employees. By keenly observing the qualities of these many sorts of samples, and taking into account the laws of probability, we can derive valuable conclusions about related things, and the future, that one not versed in statistics would never discover.

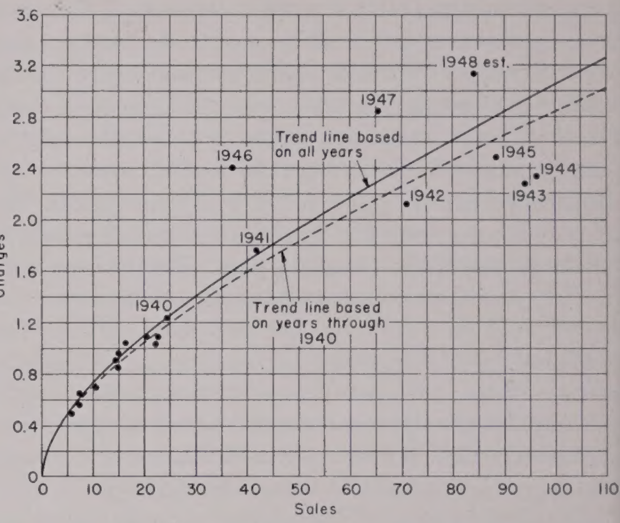

Fig. 2. Example of how closely (6 percent) a trend in Overhead Charges vs. Sales Billed over 20 years (full curve) was predicted (dotted curve) from the data of the first 12 years by using the method of least squares

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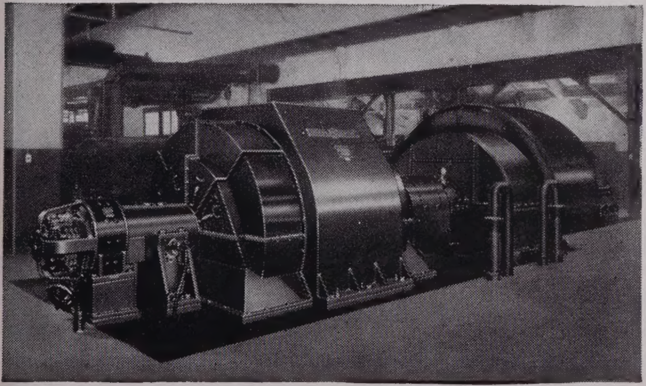

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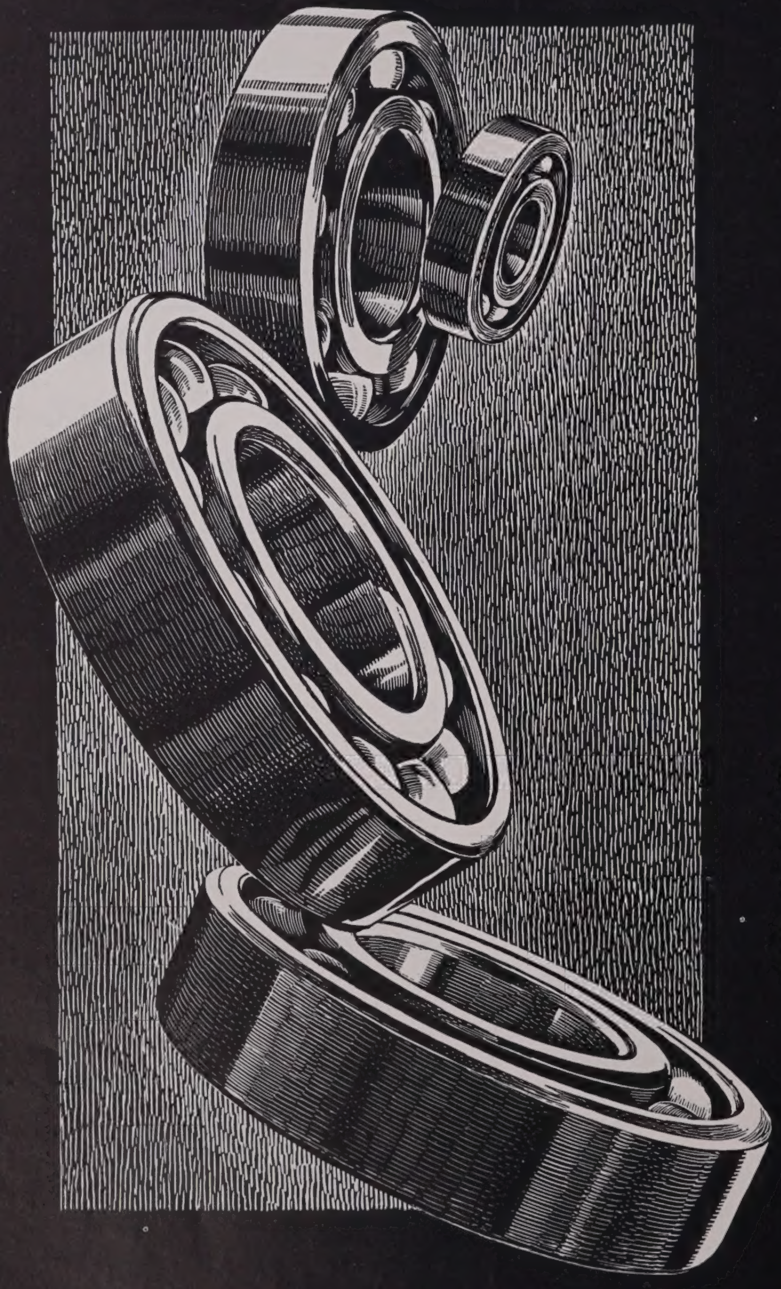

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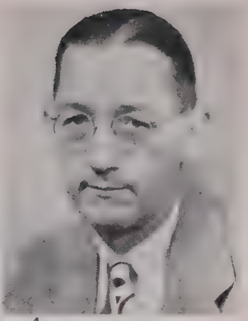
360,000-VOLT POWER TRANSFORMER

Design and construction of a 360-kv power transformer developed to investigate the design of apparatus for voltages in excess of present commercial requirements. This 10,000-kva unit withstood, without injury, 30 test impulses in excess of 1,000,000 volts

By J. R. MEADOR
Power Transformer Engineering Division
General Electric Company



J. R. Meador

BY REASON of the trend toward higher system operating voltages, General Electric has developed transformers having voltage higher than the present accepted range of commercial requirements. Recently a 360,000-volt power transformer was built at the Pittsfield Works. This represents a substantial increase over the 287,500-volt Hoover Dam transformers, the highest voltage power transformers previously built by General Electric.

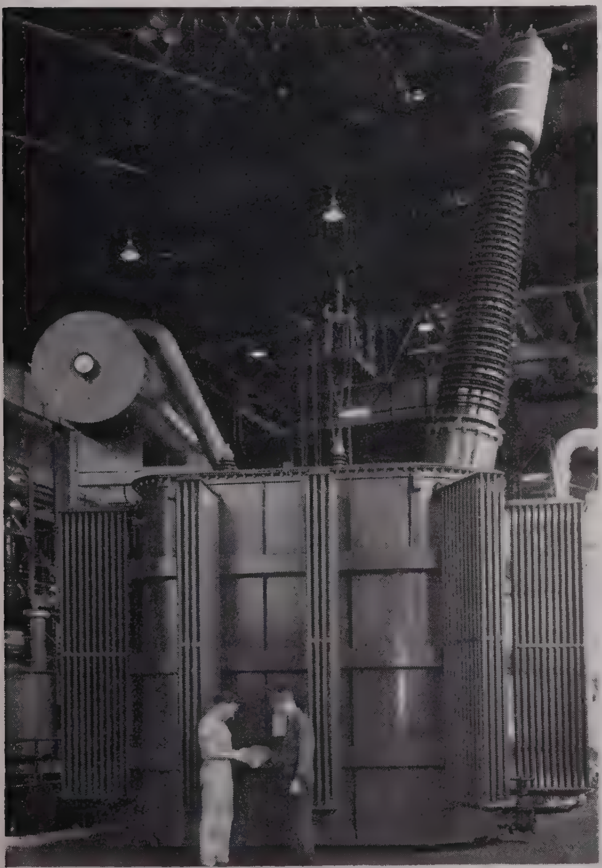


Fig. 1. Factory view of 360,000 to 13,800-volt 10,000-kva power transformer built for developmental purposes

The 360-kv transformer was designed for an induced-voltage test of 690 kv. The corresponding ASA impulse test requires the application of two chopped waves of 1785 kv and a full wave at the basic insulation level of 1550 kv. These are believed to be the highest impulse voltages ever successfully applied to a full-sized power transformer.

It now appears that apparatus for extra-high-voltage systems of the future will be designed for grounded-neutral operation and will have reduced insulation which will be co-ordinated with the protective level of the lightning arrester. Since the protective level of the arrester is directly proportional to the arrester's rating, any improvement in system operation which makes it practicable to use a lower arrester rating will also make it possible to lower the basic insulation level.

So far, most high-voltage grounded-neutral systems have used arresters whose rating is not less than 140 percent of the line-to-ground operating voltage. However, it may be feasible to control system over-voltages in the future, so that the arrester rating may be chosen on the basis of 125 percent of line-to-ground operating voltage. Under these conditions, an arrester of 360-kv maximum rating can be applied with a transformer having a basic insulation level of 1550 kv on a 500-kv three-phase system, and provide the same margin of protection for the transformer as has been demonstrated to be adequate in the past.

Many of the problems encountered in the design of very-high-voltage transformers were circumvented, to a considerable extent, by incorporating into the development a number of new practices which proved themselves in decreased bulk and weight and better impulse-voltage distribution characteristics.

TRANSFORMER DESCRIPTION

The 360-kv transformer has a continuous self-cooled 60-cycle rating of 10,000 kva, single phase, 55C winding rise. FIG. 1 shows the transformer completely assembled with its 360-kv cover bushing in place. The height over the bushing is 32 ft, 3 in., and the total weight (including oil) is 145,000 lb.

The 360-kv winding which has one end grounded is of the shielded, cylindrical-layer-winding construction, whose principal features were described by H. O. Stephens in this magazine.(1) The 13.8-kv low-voltage winding is a convention helical coil. The coils are

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(1)Numbered references are listed at the end of the article.

This article is so paged that without mutilating other articles, it can be readily removed for filing as a group of full-size consecutive pages.—EDITOR

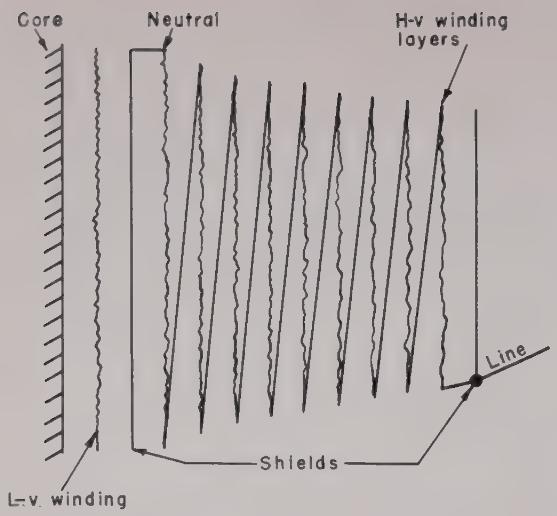


Fig. 2. Schematic diagram of shielded, concentric, cylindrical layer winding

assembled on a conventional two-legged core with windings on the two legs in parallel.

The high-voltage winding consists of a number of cylindrical layers arranged concentrically over the low-voltage winding. The innermost layer, adjacent to the low-voltage winding, is connected to the neutral; and the successive layers are connected in series progressively, the outer layer being connected to the line as shown in FIG. 2. A cylindrical shield surrounds the outer layer and is connected to the line. A similar shield, connected to the neutral, is between the inner layer and the low-voltage winding.

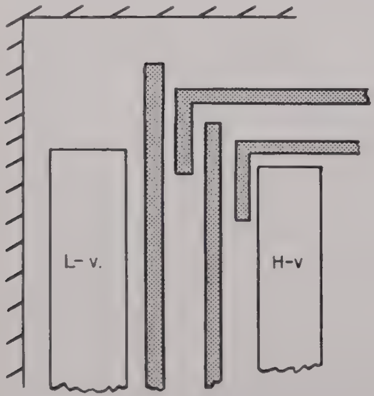


Fig. 3. Schematic diagram showing conventional insulation between high-voltage and low-voltage windings

The series connections are made from the top of one layer to the bottom of the adjacent layer. This connection substantially improves the impulse-voltage distribution compared to top-top, bottom-bottom connections and limits the layer-to-layer voltage to that of one winding layer.

Conventional transformers are insulated between windings and between parts of the same winding by either pressboard barriers or insulating cylinders (depending on the type of construction) essentially as shown in FIG. 3. Angle pieces or flanged collars provide additional creepage to avoid excessive barrier or cylinder extensions.

In the shielded cylindrical layer winding the basic insulation is the flanged cylinder which is used between the winding layers, and also between the high-voltage and low-voltage windings (FIG. 4). The insulating cylinder on which the layer is wound is flanged over the ends of the winding. The intimate contact of insulation with the winding and the elimination of creepage paths in the direction of high electrical stresses greatly improve the dielectric characteristics.

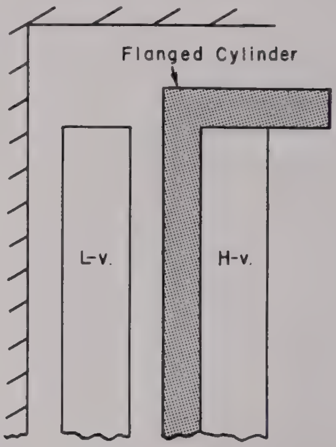


Fig. 4. Schematic diagram showing flanged cylinder insulation between high-voltage and low-voltage windings

The application of the flanged cylinder construction is shown in FIG. 5. By means of a highly developed winding technique, the entire high-voltage coil is wound as a unit having great mechanical strength. An

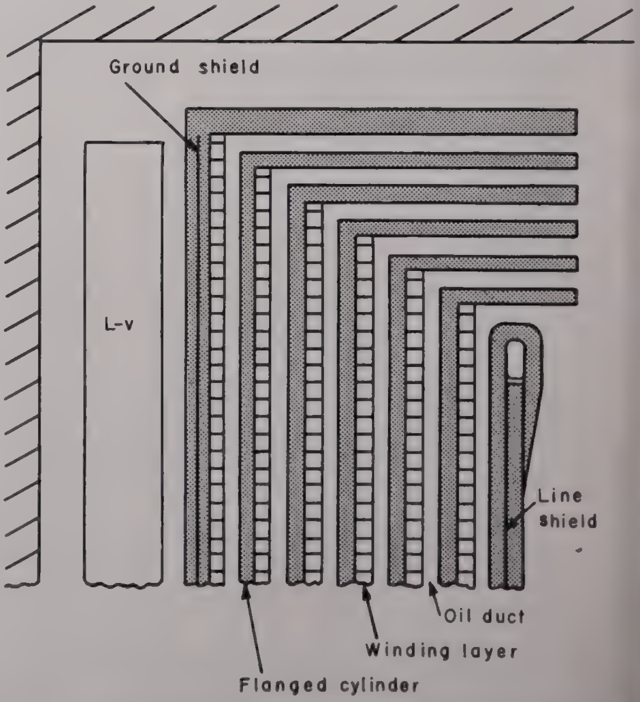


Fig. 5. Schematic diagram of high-voltage winding with six layers insulated by flanged cylinders

ingenious friction ring is used during winding to insure tightness. After each layer is wound, it is clamped tightly in place while succeeding layers are wound. The spacers that maintain the oil duct between layers are carefully aligned radially and sufficient spacers are used to assure a round coil. The layer-to-layer insulation, consisting of an insulation cylinder, is wound over the spacing strips. After winding, the coils are clamped to size before the insulating cylinders are flanged. A complete winding ready for assembly on the core is shown in FIG. 6.

There are a number of advantages in this unit construction. Handling the coil in the factory is greatly simplified, for once the coil is wound it is handled as a unit with less risk of internal damage. Many assembly tolerances are eliminated, resulting in a great increase in mechanical strength. Also, the connections are simplified and the number of connections is small; all of which adds to dependability.

Two types of conductors have been used in concentric cylindrical coils. When the high-voltage coil current is not large, a rectangular conductor is wound "on edge." This provides an excellent bearing surface for withstanding short-circuit forces in the direction parallel to the axis of the coil. For higher currents, a machine-transposed conductor is used to minimize eddy-current losses. For almost ten years a machine for continuously transposing a group of wires of rectangular cross-section has been in use. In this transposed conductor the strands are held together in such a manner that they cannot slip out of position, and the group of wires can be treated essentially as a mechanical unit in designing coils to withstand short-circuit forces.

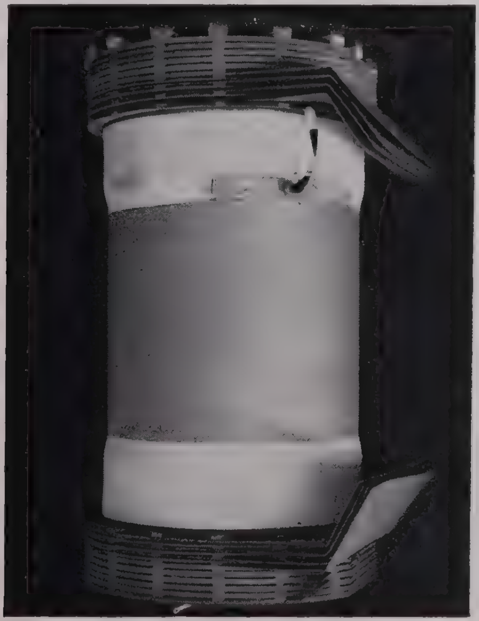


Fig. 6. Complete, shielded, cylindrical layer winding ready for assembly on a vertical-type core

When a transposed conductor is used in the shielded cylindrical layer winding, the maximum individual strand dimension is parallel with the leakage flux even though the over-all size of the transposed conductor may be much greater in the dimension perpendicular to the leakage flux. Thus, even in the largest transformers the maximum eddy-current loss (in the winding layer adjacent to the main leakage flux) is small and the mechanical strength is great.

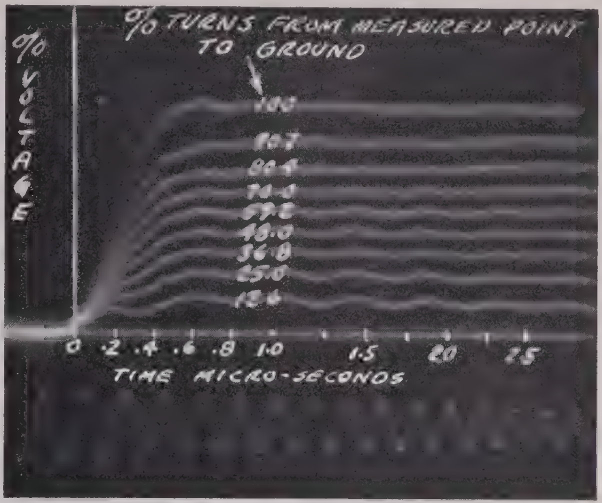


Fig. 7. Impulse-voltage distribution in 360-kv winding when 0.6×190 wave is applied to line end

In developing this type of high-voltage winding, extensive mechanical tests were carried out to determine proper conductor dimensions, method of anchoring end turns, compressibility of winding layers, etc. As a part of this program, a full-size power transformer (7.6 percent reactance) was given short-circuit tests with fully maintained primary voltage. Some of the full kva short circuits were made with portions of the winding tapped out to give a magnetic unbalance far in excess of that ever used. After all tests were completed the high-voltage winding was completely unwound. There was no evidence of distortion in the winding or insulation structure, indicating the soundness of the design.

IMPULSE-VOLTAGE DISTRIBUTION

When an impulse voltage is applied to the line terminal of a winding, it is initially distributed through the winding essentially in accordance with the electrostatic field. In the shielded cylindrical layer winding, the relative positions of the layers are such that the potentials they assume, in the surge-produced electrostatic field between line and neutral shields, are not far removed from the normal low-frequency potentials. Since the initial impulse voltage is quite uniform, the subsequent oscillations are minor. This is illustrated by the oscillogram in FIG. 7, which is of a 0.6×190 microsecond impulse wave as applied to the line end of the winding. The oscillogram recorded the voltage to ground at approximately equally spaced points in the winding. The absence of large oscillations and the relatively uniform gradations in voltage are indicative of the excellent impulse-voltage distribution.

COOLING

In this type of winding every layer is cooled by a generous ventilating oil duct. The oil enters through a horizontal duct in the insulation at the bottom, passes unrestricted upward along the winding and emerges through a top horizontal duct. Every turn is cooled by direct contact with oil.

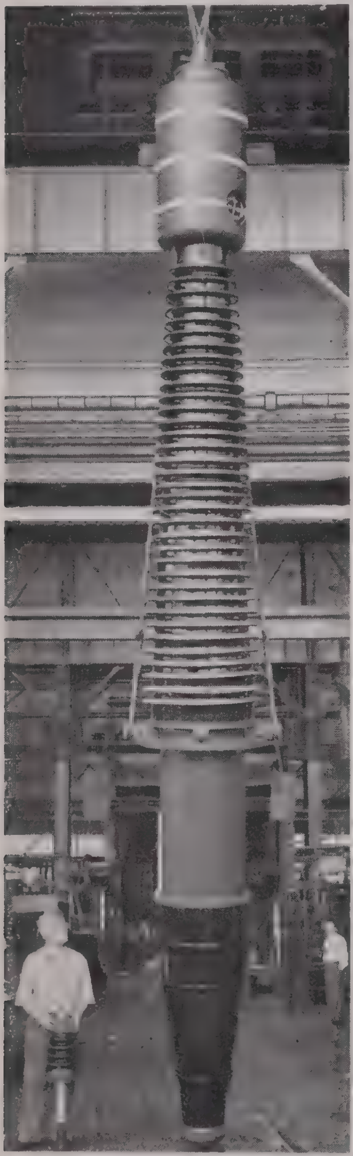
Even in large transformers, because of the transposed cable already mentioned, eddy losses are small and hot-spot temperatures are not a problem.

In transformers designed for forced-oil cooling, the advantage of a free and uniform path for the oil flow is obvious.

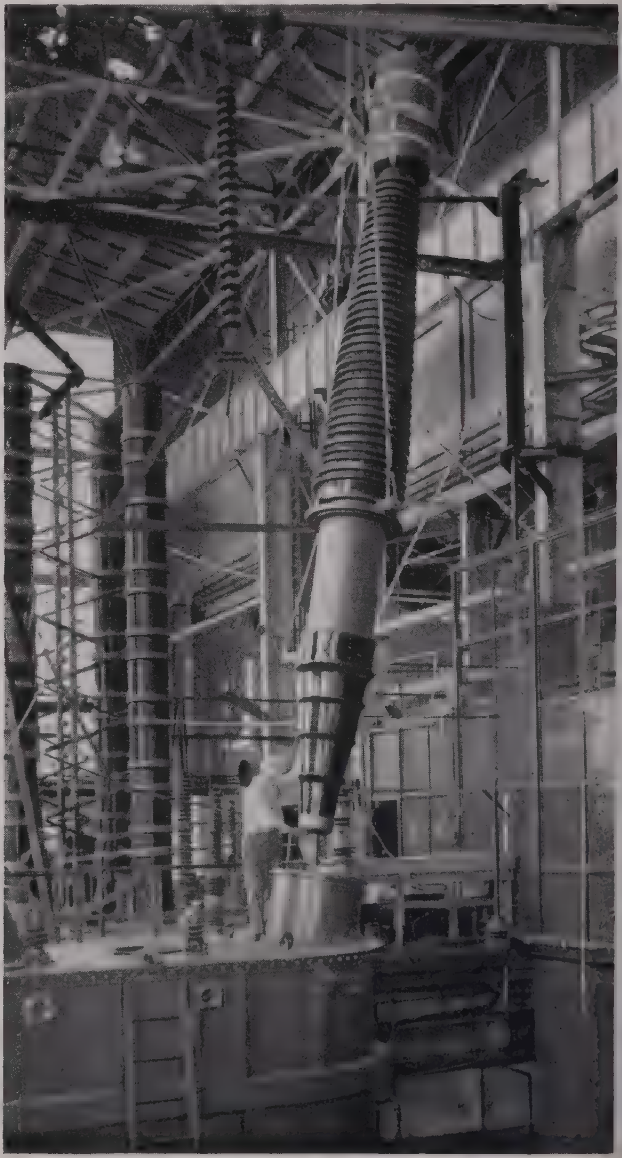
BUSHING

The bushing of the 360-kv transformer is of the new Type F, center-clamped, sealed, pressure-tight construction.(2)

Bushings of this new type are sealed at the factory and are carefully processed to assure high quality of all the internal insulation before the final seal is made. They are centrally clamped through a center tube and constant pressure is provided by a multicoil spring assembly located in the top of the bushing. An adequate expansion space is provided in the top metallic dome and a magnetic liquid-level device indicates the level of the liquid in the bushing.



← Fig. 8. Comparative size of the transformer's 360-kv bushing and a 34.5-kv bushing (at lower left)



→ Fig. 9. A 360-kv bushing being lowered into position on transformer. Impulse testing equipment is shown in the background

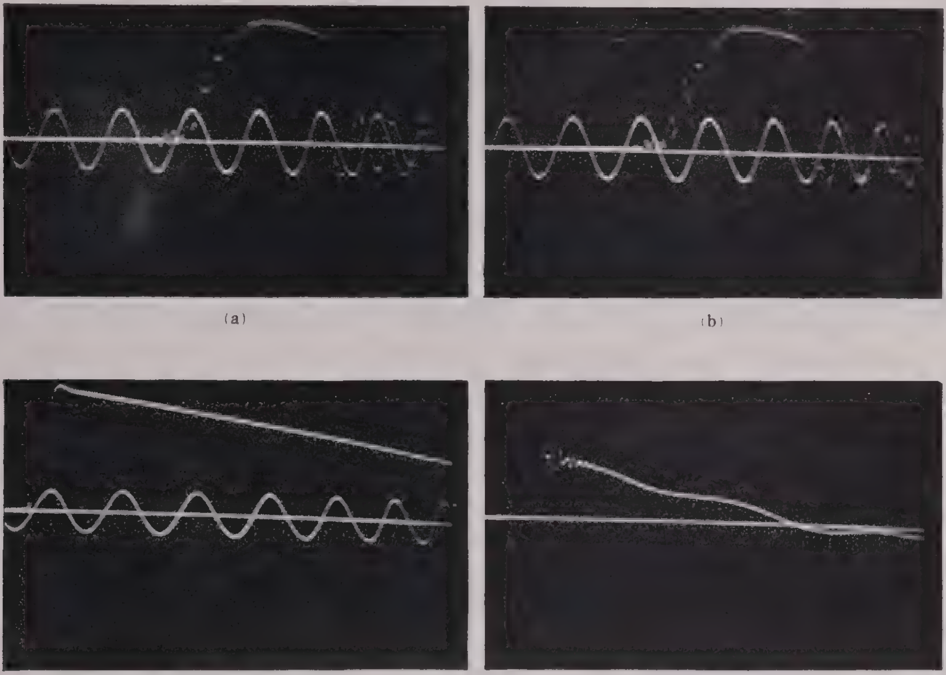
The 360-kv bushing is approximately 26 ft long and weighs approximately 8000 lb when filled with oil. Fig. 8 contrasts the size of this bushing with that of a 34.5-kv bushing of the Type L construction. Fig. 9 shows the 360-kv bushing being lowered into position on the transformer.

IMPULSE TEST ON TRANSFORMER

During the testing of this transformer, 30 impulses in excess of 1,000,000 volts were applied without injury.

The oscillograms of the final four impulses are shown in Fig. 10.

By comparing the full wave (FIG. 10(c)) and its corresponding neutral current wave (FIG. 10(d)) with the comparable oscillograms taken previously in the tests at lower voltage, it was evident that the transformer had not been damaged by the many tests applied. On none of the tests was there any noise in the tank or any disturbance in the oil.



(a) (b) (c) (d)

Fig. 10. Oscillograms taken during impulse test on the 360-kv transformer
(a) and (b) Chopped wave of 1,785,000 volts
(c) Full wave of 1,550,000 volts
(d) Neutral current at 1,550,000 volts

ADVANTAGES OF SHIELDED, CYLINDRICAL-LAYER CONSTRUCTION FOR WYE-CONNECTED TRANSFORMERS

The principal advantage of this construction is the virtual elimination of the "major" insulation between high-voltage and low-voltage windings of grounded wye transformers. This advantage permits substantial reductions in the amount of steel required for the core. The higher the line voltage, the greater is this gain, since high voltage is achieved merely by adding winding layers *outside* of the existing winding.

Flanged-cylinder insulation keeps all dimensions to the minimum. Even where the neutral is not solidly grounded, the high-voltage-to-low-voltage spacing is smaller than with other constructions.

The unit construction of the high-voltage winding eliminates assembly tolerances.

All turns are in contact with cooling oil; and the winding hot spot is mainly a matter of oil gradient in the tank.

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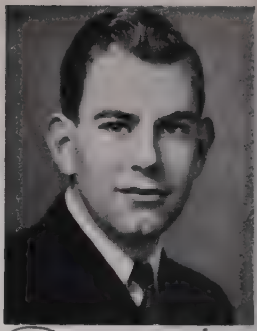
MECHANISM OF DIELECTRIC BREAKDOWN

Theoretical approach to the problem of insulation failure resulting from breakdown of gaseous dielectrics, liquids, and solids. Conclusions applicable to research and practice



Dallas T. Hurd

By DR. DALLAS T. HURD
Research Laboratory, General Electric Company

INSULATION is a problem which confronts the electrical industry in almost every phase of its operation, yet today insulation engineering is still a highly empirical art, particularly in regard to the important considerations of dielectric strength and insulation failure.

This situation is not surprising when one considers the confusing amount of data that has been collected on dielectric materials, much of which is inexact and meaningless, and the numerous conflicting theories that have been proposed to explain dielectric breakdown and failure of insulation.

In view of the vast practical importance attaching to the dielectric strength of insulating materials under steady and impulse voltages, the author has endeavored to introduce the more prominent theories in this field, and to draw general conclusions that may be applicable to insulation research and practice.

BREAKDOWN OF GASEOUS DIELECTRICS

As an introduction to the subject of insulation failure, we shall consider first the electrical breakdown(1) of a gaseous dielectric at atmospheric pressure under voltage stress. This phenomenon appears to be fairly well understood and there is general agreement among authorities as to the mechanism of breakdown. It provides a good starting place from which we can extrapolate to explain the behavior of liquid and solid dielectrics.

FACTORS AFFECTING BREAKDOWN STRENGTH

A number of primary effects are observed when samples of gas are placed between electrodes and subjected to voltages increasing up to the breakdown point:

(1). All other conditions being equal, the breakdown voltage of the sparkgap is approximately proportional to the distance between the electrodes and to the pressure of the gas. That is, V_b is proportional to PD where V_b = breakdown voltage, P = gas pressure, and D = separation of the electrodes. This relationship is illustrated in Fig. 1. Note that it does not hold for very small values of PD. Below a certain minimum value of PD, the breakdown voltage rises sharply as the value of PD becomes smaller.

(2). The breakdown voltage is highly dependent on the physical character of the electrodes. With electrodes ending in sharp points or having sharp irregularities on their surfaces, lower breakdown voltages are observed than with smooth spherical electrodes. For example, the breakdown voltage of air between spherical electrodes is about 30 kv per centimeter, whereas less than 15 kv is needed to rupture a gap of one centimeter between needle electrodes. Surface impurities on the electrodes, such as oil, dust, etc. also can lower the breakdown voltage.

(3). The breakdown voltage is also dependent on the nature of the gas between the electrodes. Nitrogen, for example, has nearly twice the dielectric strength of hydrogen. Other gases, in particular those containing a large proportion of halogen, such as the Freons and sulfur hexafluoride, may have dielectric strengths several times greater than that of nitrogen.

(4). A definite time lag occurs between the application of a voltage sufficient to effect breakdown and the actual spark discharge. This time lag is decreased as the applied voltage is increased over the minimum breakdown value. It may vary from several seconds for voltages in the immediate neighborhood of the minimum breakdown value to a few microseconds, if the applied voltage is sufficiently high. Once the breakdown process is started, rupture of the dielectric generally occurs in an extremely short period of time, measured in microseconds.

(5). Increasing the frequency of applied a-c voltage decreases the breakdown strength. This effect becomes more pronounced as the distance between the electrodes is made greater. At ordinary power frequencies, however, the breakdown voltage is essentially independent of frequency.

BREAKDOWN MECHANISM

An electronic mechanism explaining the electrical breakdown of gases has been developed gradually through the contributions of a large number of investigators, and it accounts reasonably well for the observed phenomena. This mechanism is described at considerable length in comprehensive texts on gas-discharge phenomena such as that by Loeb(2). Briefly, it is summarized as follows:

A free electron in the gas space between charged electrodes is subjected to an acceleration proportional

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(1) See Notes and References at end of article—Ed.

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to the field strength and in the direction of the field. The amount of energy an electron can acquire by acceleration in the field will depend, then, on two factors: the field strength, and the distance the electron can travel before it strikes a molecule of the gas. Because the mean free path between molecular collisions is inversely proportional to the gas pressure P, and the field strength is inversely proportional to the spacing of the electrodes D, the experimentally determined relationship $V_b \propto PD$ shows that the breakdown voltage represents a lower limit of energy which, on the average, electrons must gain between their collisions with gas molecules, if breakdown is to occur.

In air at atmospheric pressure, electrons have a mean free path of about 10^{-4} cm, and the breakdown strength of air at this pressure is about 3×10^4 volts per centimeter. Hence, on the average, several volts of kinetic energy will be obtained by the electrons between successive impacts with gas molecules as the electric field approaches the breakdown strength value. If the electrons gain sufficient energy between impacts, they are able to ionize the gas molecules they strike; thus they release additional electrons, which in turn may be accelerated to ionizing energies. This electron multiplication, or chain reaction, is the beginning of an *electron avalanche*, a process which, as we will see, may result in an electrical breakdown and discharge across the gap between the electrodes.

It is pertinent to point out here that even with no applied field there probably are some free electrons in the gas with sufficient kinetic energy to ionize a gas molecule on impact; the number of such electrons will ncrease with the applied field. In view of this, it may seem surprising that the breakdown voltage of a gas, such as air, is as sharply defined and reproducible as t can be under careful test conditions.

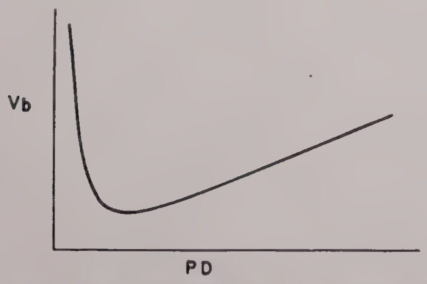


Fig. 1. Curve showing breakdown voltage as a function of pressure and electrode spacing

However, for electric fields below the breakdown strength, there remains a very effective barrier against the acceleration of electrons, and the ionization that does occur under these conditions remains insufficient o cause electron avalanche and breakdown. Inelastic mpacts between electrons and gas molecules occur which transfer the accumulated kinetic energy of the electrons into excitation of the electronic system of the gas molecules without causing ionization. This energy, reappearing as radiation of heat or light, or causing dissociation of the gas molecules, will normally be lost as far as ionizing the molecules to produce additional electrons is concerned. The probability of these inelastic collisions is relatively large, since many electronic transitions exist below the ionization potential level; that is, there are many ways in which a molecule can soak up the energy of an electron striking it. We will refer to this later as electrical "friction."

If we look more closely into the mechanism whereby the transfer of energy to gas molecules from colliding electrons is effected, we find that the amount of energy transferred per collision is a function of the electron's velocity. This function is illustrated in FIG. 2 which shows that there is a certain electron velocity at which the energy lost per collision is a maximum. Although this energy "barrier" is steep, if an electron is accelerated over the "energy hump," it encounters less resistance and its acceleration by the field up to ionizing energies becomes more probable. This barrier to electron acceleration, together with the exponential nature of the electron-multiplying chain reaction (avalanche), defines the threshold breakdown voltage(3) within fairly narrow limits.

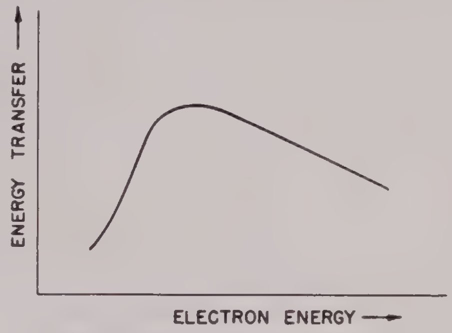


Fig. 2. Curve showing dependence of energy transfer on electron energy

ELECTRON AVALANCHE DEFINED

We have mentioned that when electrons can acquire sufficient energy by acceleration in the electric field to ionize gas molecules, an electron avalanche may start by a chain reaction. Assuming an electron in a field sufficiently high, we can reason as follows: The electron is accelerated toward the anode, ionizing as it goes. In a few millimeters, it has produced some hundreds or thousands of new electrons and ions. These electrons are concentrated along a narrow path in the direction of the field and, because of their high mobility, they move on and leave behind less mobile clouds of positive ions. These space charges of positive ions and electrons cause distortion of the field and enhance further ionization along the axis of the avalanche. The electrons formed near the anode are removed by this electrode; and the positive ion space charge that results forms a virtual extension of the anode into and across the gap. This increases the voltage stress across the remainder of the gap. Eventually, a conducting path of ionized gas is established between the electrodes, electron emission from the cathode ensues by positive ions moving into and bombarding this electrode, and the discharge becomes self-sustaining.

It is not possible to explain the rapidity of the breakdown process in gases, however, by assuming that the first electrons traverse the whole gap. The initial breakdown of the gap, once it actually starts, generally occurs at tremendous speeds (measured by experiment to be as high as 10^8 cm per sec) and electron velocities, even under the breakdown field, are not adequate to cover the gap in the observed breakdown times. It has been postulated by Loeb(2) and others that the gap actually is bridged by photons generated in the initial avalanche. These photons move out in all directions with the speed of light, and perhaps there are several times as many photons generated as there are ions formed. Although most of these photons do not have enough energy to ionize gas molecules, a certain fraction will be able to cause ionization. Most of the photons are able to eject photoelectrons from the electrodes. Thus, almost simultaneously with the original avalanche, new electrons created by photoionization are starting avalanches both from the cathode and from the head of the original avalanche along the breakdown path because conditions are most favorable for ionization in this direction. By such a means, very high-speed propagation of electrical breakdown in gases is believed possible by a step-wise series of avalanches seeded by photoelectrons.

FACTORS NECESSARY FOR BREAKDOWN

Additional characteristics of this mechanism must be pointed out before proceeding further. For actual electrical breakdown of the gaseous dielectric to occur, it is necessary that:

(a). The voltage stress be above the threshold value. Below this value, conditions are not favorable for the formation of electron-multiplying avalanches.

(b). A free electron must appear in the gap and begin an electron avalanche by cumulative ionization. This electron can appear by photoionization of the dielectric by light or other radiation, by thermal ionization of a gas molecule, by field emission from an electrode, etc.

(c). Its progeny (including electrons formed by photoionization) must cross the gap and in the process produce a sufficient number of positive ions and electrons to make the gap conducting; that is, a continuous conducting path of ionized gas must be set up extending from anode to cathode.

(d). An efficient source of electrons must be established at the cathode to maintain the supply of electrons; otherwise, the conducting particles will be swept out of the gap by the field, and the gas will become nonconducting again.

All those criteria must be satisfied if breakdown is to take place with the discharge of appreciable currents through the dielectric. It has been shown for voltages in the neighborhood of the intrinsic breakdown strength that the occurrence of breakdown is a statistical phenomenon—that is, one dependent on the occurrence of a series of events. Avalanches may occur that do not succeed in bridging the gap with a conducting ionized path, and a conducting ionized path may fail to result in breakdown by failure to establish an emission of electrons by the cathode. The probability of breakdown, however, increases rapidly as the voltage is raised above the threshold breakdown value. This statistical nature of the breakdown process explains in part the time-lag effect observed in breakdown measurements and the variation in minimum breakdown voltage observed in dielectric-strength tests.

EFFECT ON BREAKDOWN PHENOMENA

Let us return and examine in the light of this mechanism some of the effects enumerated previously.

(1). We have seen that the dependance of the breakdown voltage on the value of *PD* is a consequence of the electronic nature of the initiation of the breakdown. If we want higher breakdown strength in a gaseous dielectric, we can get it by going to higher gas pressures, or by moving the electrodes further apart. If the distance between the electrodes is made very small—that is, in the order of magnitude of the mean free path—then the breakdown voltage rises sharply with decreasing spacing. This is because the number of ionizing impacts that one electron can effect in moving between the electrodes becomes extremely limited. Consequently, it becomes more difficult to get sufficient ionization to make the gap conducting.

(2). It can be shown that the local fields in the neighborhood of sharp electrode points may be sufficiently strong to cause electrical breakdown of the gas in those regions, even though the over-all potential across the gap between the electrodes is far below the breakdown strength in terms of volts per centimeter. This breakdown in the neighborhood of the electrodes may propagate through the gap to result in dielectric failure at voltages much lower than the normal breakdown strength. Another phenomenon associated with the high fields in the neighborhood of sharp points is the emission of electrons. This is known as "field emission" or "cold emission," and it may supply electrons to initiate a discharge across a gap.

(3). The reason that one gas may show a higher dielectric strength than another is presumed to lie in the relative ability of the gas molecules to absorb energy from impacting electrons, or to remove electrons from the ionization processes by attaching them with the formation of relatively stable negative ions.(4) The latter effect is especially true of electronegative gases, such as the halogens. Compounds, such as CCl_4, CCl_2F_2, $C_2Cl_2F_4$, SF_6, etc., release halogen atoms by dissociating in the path of the discharge. These electron-greedy halogen atoms attach free electrons to form halide ions which are difficult to break up again and which drift out of the path of the discharge. This in effect raises the average energy required by free electrons to cause cumulative ionization, and also may aid in breaking up incipient electron avalanches. The Freon gases have very high dielectric strengths.

(4). We previously have observed that the occurrence of breakdown is a function of the probability of several events, and that increasing the applied voltage above the threshold value increases the probability of these events' occurring. Thus, at higher voltages, we find shorter time lags between the application of the voltage and dielectric failure. Another source of the time lag is inherent in the mechanism of breakdown; that is, it takes a short but finite time for the conducting path to be set up in the gas and for secondary electron emission to start at the cathode.

(5). The variation in breakdown strength with the frequency of the applied voltage is a complex phenomenon related to space-charge effects and will not be considered here, because at ordinary power frequencies the breakdown voltage is essentially independent of frequency. This effect becomes important when the field-reversal time, as determined by the frequency, reduces to the same order as the transit time of the breakdown process through the dielectric.

Extrapolation to Solids—Breakdown of Ionic Crystals

In gaseous dielectrics, electrons are prevented from accelerating to ionizing velocities by inelastic impacts with the gas molecules in which the kinetic energy of the electrons is transferred into the electronic system of the gas molecules as excitation energy. In air at atmospheric pressure, the mean free path is about 10^{-4} cm and we need a field strength of about 30,000 volts per centimeters, or on the average about three volts per mean free path length, to accelerate electrons to the point where cumulative ionization can occur. Only beyond this value can we expect breakdown to be possible.

If we extend this type of reasoning to liquid and solid insulation, we would expect, considering the mean free path lengths in such substances, breakdown fields of the order of 60 million volts per centimeter, a value some fifty to one hundred times too large. This is a serious discrepancy, and much effort has gone into elaborating an explanation.

INTERNAL ENERGY BARRIERS

The modern theories of electrical breakdown in solids have been led by the careful work of Von Hippel(5) on the breakdown of alkali halide crystals. The general line of reasoning is as follows:

Dielectric breakdown in solids can be presumed to follow the same sequence of events as breakdown in gases but with one important difference. Whereas the loss of energy by electrons in excitation of the electronic systems of gas molecules provided a very effective barrier in protecting gases against breakdown below the threshold breakdown voltage, this mechanism of "friction" loses much of its importance in condensed systems. The influence of neighboring particles lowers the ionization potential of a molecule or ion in a solid so much that an excitation of the electronic system becomes practically equivalent to ionization. In other words, the electronic systems of the molecules in a solid do not provide a sink to drain off the energy of the impacting electrons as they do in gases. If energy is adsorbed in this fashion from the impacting electrons, the result usually is ionization, which in turn may lead to breakdown. This situation also holds for liquids.

However, below the barrier of excitation of molecular electronic systems, there lies a second barrier that is efficient in stopping slower electrons. This is in collisions which excite vibrations or oscillations of the molecules. It can be shown mathematically that the probability of an electron losing energy to a molecule in this fashion also is a function of its velocity, and that there is a certain electron velocity at which the transfer of kinetic energy in exciting vibrations of the molecule is a maximum (a function similar to that shown in Fig. 1). As the velocity of the electron approaches the critical value, more and more energy is transferred on impact with a molecule. As the electron energy exceeds this value, the degree of "coupling" or energy transfer decreases. Thus, if the electron can gain sufficient energy between impacts to get over the "hump" of the vibrational energy-adsorption curve, acceleration becomes easier.

This type of friction is not important as far as the breakdown strength of gases is concerned. On the average, the electrons can gain so much energy across one free path that they are far above the maximum adsorption energy for vibrational excitation and lose very little of their kinetic energy by this mechanism. For liquids and solids, however, the situation is quite different. Here the colliding electron is not coupled with only a few atoms, as in a gas molecule, but with a great number of molecules because of the interaction of the molecules with each other. The barrier of oscillations thus is broadened and increased in effective "height." We should expect, therefore, in liquids and solids that the friction losses suffered by electrons in exciting molecular vibrations will determine the threshold breakdown strength, since the electronic barrier, operative in gases, is not effective in liquids or solids.

THEROY TESTED

Von Hippel(5) selected single crystals of the alkali halides to test this theory. The alkali halides are very good insulators; they crystallize in simple ionic lattices and, most important from the standpoint of the theory, sufficient is known about the vibrational spectrum of these crystals (from spectroscopy) to make possible an approximate calculation of the value of maximum energy transfer—that is, the highest point on the barrier—and a prediction of the breakdown voltage for a given crystal. A number of alkali halides were tested and the measured breakdown strengths were compared with values estimated from infrared vibrational data. The agreement was surprisingly good, sometimes being within 30 or 40 per cent of the estimated values.

Von Hippel found it possible to follow the path of the breakdown as it developed along preferred crystal planes in an alkali halide crystal, and he made several observations that may be useful in considering other materials. With point electrodes inserted into the crystal, the voltage applied was of such a value that only in the neighborhood of the electrode points was the crystal subjected to breakdown stress. The tracks of positive space charges formed by successive electron avalanches in the crystal followed a bending path from the anode through the crystal along crystal diagonals and, acting as an extension of the anode, bridged the gap step by step in rather large steps. Under the heating influence of the current, the corners of the track, sharply rectangular at first, became rounded and smooth. If a plate of crystal is placed between plane electrodes and the whole crystal subjected to breakdown stress, the situation is somewhat different. At breakdown, the development of the positive space charge and the virtual extension of the anode into the crystal by the space charge changes the geometry of the field, and very high fields result at the head of the space charge. Because of these very high local fields, the breakdown occurs very fast in a large number of small steps.

Von Hippel also showed that some free electrons might be expected to exist in alkali halide crystals at all times, and that electron emission from the cathode into the crystal can take place. Thus, the major requirements for breakdown to occur are satisfied. It may be seen then, that, except for the different barrier presented to electron acceleration, the mechanism of breakdown for ionic solids is analogous to that in gases.

To recapitulate: Electrons traveling through a crystal with kinetic energies below the maximum of the barrier will lose their energy repeatedly in their impacts with the ions of the crystal, exciting these to vibrations. Thus, the electrons are prevented from accelerating to ionizing energies. The critical field strength is reached when the barrier or "resistance" is a maximum and the vibrating ions in the crystal are soaking up energy from the electrons at the maximum possible rate. Stronger fields can drive electrons across the point of maximum resistance, the average loss of energy by impact decreases with increasing electron velocity, and the situation becomes favorable for cumulative impact ionization—that is, an electron avalanche.

As previously stated, an electron avalanche in a gas does not necessarily result in breakdown, unless the positive ions eventually reach the cathode to start secondary emission to maintain the discharge. The situation is different in solids because the positive ions are more or less fixed in position. The electrons formed by ionization are swept out by the field, leaving the positive ions behind. This stationary space charge distorts and intensifies the field, and weakens or destroys the physical structure of the material, both favoring the further progress of breakdown. Hence, the start of cumulative ionization in solids is the beginning of dielectric breakdown.

One consequence of the theory is that, if the dielectric is so very thin that its thickness approaches the mean free path length, the dielectric strength should increase. Experiment has shown this to be true for extremely thin sections of mica. It may be recalled that this also was true for gases.

Von Hippel's ideas on breakdown mechanism have been modified and expanded by Seeger and Teller(6), Fröhlich(7), and others into formulas that have been used with remarkable success for calculating the breakdown strengths of ionic crystals. Frequently, estimated values within a few per cent of the observed breakdown voltages have been obtained. These formulas, representing refined methods of calculating the internal energy barriers presented by ionic solids to the acceleration of electrons, are complex functions involving physical constants of the particular material under consideration.

Extrapolation to Liquids—Breakdown of Carbon Tetrachloride

Attwood and Bixby(8) have applied the general mechanism considered in the previous section to the electrical breakdown of carbon tetrachloride. They assumed in making their calculations that carbon tetrachloride was ionic, comprising a central carbon charged to four positive units surrounded by four chloride ions, since the theories extant were developed for ionic crystals. Then, using the theories developed by Seeger and Teller(6) and Fröhlich(7), they calculated values for the breakdown strength of carbon tetrachloride and compared these with the values which they obtained in careful breakdown tests on the pure material. These values agreed within a factor of two or three and, if certain reasonable assumptions were made in interpreting the formulas, the agreement was much closer.

Attwood and Bixby also made some interesting observations on the time-lag effect in breakdown. It can be seen from FIG. 3 that slowly applied fields give breakdown voltages F_b which vary but little and approach asymptotically the critical value F_∞ representing the intrinsic electric strength of the dielectric. As the impulse field is applied more and more rapidly, the overvoltage (F_b–F_∞) increases markedly, while the time lag—that is, the time between when the voltage reaches the value of F_∞ and the occurrence of breakdown—declines only slightly. Attwood and Bixby were able to show that the time lag for carbon tetrachloride followed a simple rule in its dependence on overvoltage. This was derived on the assumption that the breakdown follows a course similar to that postulated for breakdown in gases and ionic crystals; that is, the stepwise growth of a positive-ion space charge forming a virtual extension of the anode into the dielectric and intensification of the field at the head of this charge.

THEORETICAL SEQUENCE OF DIELECTRIC BREAKDOWN

The approaches that have been made to the problem of dielectric breakdown from a theoretical viewpoint would indicate that the same *sequence* of events probably occurs in any dielectric—liquid, solid, or gas—

that fails under electrical stress. Briefly, these steps are:

(1). Occurrence of a free electron or electrons in the dielectric.

(2). Acceleration of free electrons in the dielectric by the applied voltage to energies sufficient for cumulative impact ionization. This acceleration must be sufficient to overcome the energy barriers protecting the dielectric from breakdown. These barriers are the vibrational energy levels of the molecules or ions in condensed phases, and the electronic energy levels of the molecules or ions in gases.

(3). Cumulative impact ionization and the formation of electron avalanches that sweep through the dielectric.

(4). Removal of electrons by the field, leaving behind a less mobile space charge of positive ions.

(5). Growth of the positive space charge as a virtual extension of the anode through the dielectric, thus establishing an ionized path through the dielectric, and actual physical destruction in solid dielectrics.

(6). Emission of electrons from the cathode to maintain the discharge.

Calculations of intrinsic breakdown strength generally must be based on Step (2). This is more or less logical since the energy barriers with which the molecules of the dielectric can confront rapidly moving electrons are the only lines of defense which dielectrics have *per se* against breakdown. In some dielectrics, the mechanism of electron capture by electronegative atoms can increase the average electron energy requirement necessary for cumulative ionization.

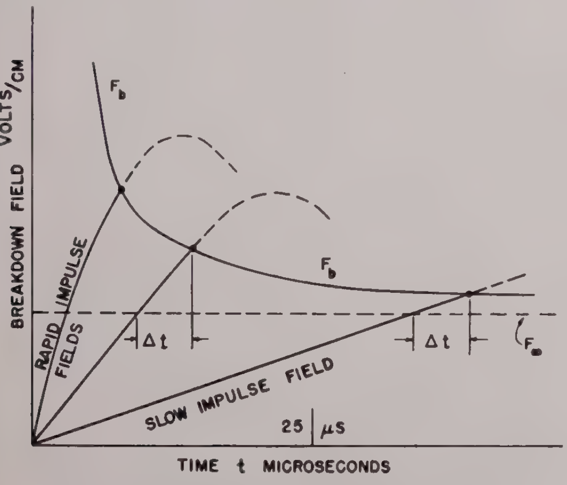


Fig. 3. Curve showing time dependence for impulse fields

Predictions of breakdown occurrence must take into account the remaining steps. In actual practice, one or more of these generally is the deciding factor whether breakdown will occur as the voltage is raised above the critical value necessary for breakdown. Since breakdown depends on the happening of a number of events, its occurrence is a statistical function—that is, highly dependent on probability. We will see later how this affects the measurement of the breakdown strength of commonly used insulating materials.

The older theories of electrical breakdown are notable chiefly for their failure to predict even the correct order of magnitude of breakdown voltages. Certain of these theories assumed that breakdown is due to the ionization of molecules by moving ions carrying a current. Modern views of ionic conduction make it highly doubtful whether ions could acquire the necessary energy in liquids or solids for impact ionization, or complete the breakdown processes in the very short times actually observed. It seems almost certain now that the breakdown mechanism is electronic in character.

Application of the Theory to Insulating Materials

Thus far this has been a theoretical approach to the behavior of comparatively simple materials. The practical application of the theory of dielectric breakdown to conventional insulating materials is often complicated by a phenomenon known as "thermal instability" or "heat breakdown."

THERMAL INSTABILITY

Insulating materials generally show a decrease in breakdown strength with increasing temperature, and considerable effort by a number of investigators has been devoted to explaining insulation failure on this basis. The term "heat breakdown" actually covers a number of factors which may weaken the breakdown strength of a dielectric.

An electric field established in a dielectric leads to losses which raise the temperature of the dielectric. This heating effect may be of two kinds: that due to actual conduction in the dielectric, and that due to dielectric losses in a-c fields. The former effect would be absent in a perfect insulator in d-c fields. However, few insulating materials are perfect insulators. The dielectric system is stable thermally as long as the rate of heat dissipation is greater than the rate of heat generation; otherwise, the temperature will continue to rise until the dielectric fails. The thermal breakdown process essentially is a slow one, and a field in the neighborhood of the threshold breakdown strength may require hours to produce puncture. The electrodes, the ambient temperature, the thermal conductivity of the dielectric, and the nature of the surroundings all play an important part in this process.

Closely allied with thermal instability are the deleterious chemical effects in the dielectric caused by the conduction of electricity through it, as well as by high temperatures. Since the conductivity of a slightly conducting dielectric will usually increase with an increase in field strength, this effect can be expected to become more pronounced with higher field strengths.

It should be noted, however, that "thermal instability" is not a different type of breakdown from the general picture we have been considering but rather represents a mechanism for initiating one or more of the several steps necessary for breakdown according to the general scheme, and for lowering the breakdown strength by deterioration of the dielectric. It is limited, in general practice, to unfavorable circumstances, such as high ambient temperature, high power factor, low thermal dissipation, great insulation thickness, and poor insulating properties.

EFFECTS OF THERMAL INSTABILITY

Under the influence of conductivity and increasing temperature, several things may happen: Electron emission from the cathode may start; increase of cold or field emission from the cathode may distort the field distribution in the dielectric and increase the local field strength; the increasing mobility of the positive ions with temperature may do the same thing; and in many materials chemical decomposition and oxidation will contribute to lowering of the breakdown strength. It must be remembered that electrons moving in an electric field can be a very powerful chemical reagent.

In dielectrics where conductivity and dielectric losses are small, thermal instability generally is not involved in breakdown.

PROBLEM OF MEASURING BREAKDOWN STRENGTH

If one seriously considers the large number of factors that can influence the initiation of breakdown, such as emission of electrons from rough or dirty electrodes, dielectric losses in the insulation, chemical changes in the insulation, etc, as well as the several previously mentioned factors that must be satisfied for breakdown to occur, it becomes clear that electrical breakdown is a statistical phenomenon whose probability depends on a great many different factors; and no one is going to be able to take a given insulating material and say, *a priori*, just what its measured breakdown strength will be, or even come close. Although, if enough of the conditions are specified, it may be possible to guess within a factor of two for very pure materials. By the same token, it does not seem probable that any meaningful correlation can be given to comparative dielectric breakdown tests on different materials unless the test conditions are very carefully controlled, exceptionally pure materials are used, and the average breakdown values obtained in a large number of tests differ by a significant amount.

We can, however, look to the factors involved in dielectric breakdown with some idea of improving the performance of present-day insulating materials.

INCREASING BREAKDOWN STRENGTHS

Since the initial stages in the breakdown process involve the acceleration of free electrons in the dielectric to the point where cumulative ionization becomes possible, measures that reduce the appearance and acceleration of electrons should result in increased breakdown strengths. In liquid-filled apparatus, such as transformers, a polishing of all potential surfaces in contact with the liquid would reduce the possibility of cold or field emission from metal surfaces that ordinarily are rough and dirty.

Smoothing and cleaning of the metal surfaces in contact with the dielectric also would help in avoiding local regions of high voltage stress. In the neighborhood of sharp electrode surface irregularities or points, the local fields may exceed the breakdown strength of the dielectric, even though the over-all applied voltage is well below the breakdown value. As we have seen, local breakdown resulting from high local fields may be propagated through the dielectric, causing dielectric failure at relatively low voltages compared to the intrinsic breakdown strength. Equipment design must take this effect into consideration to avoid regions of high local field in the dielectric.

High local fields may result also from other causes. The increased mobility of ions as the temperature increases, together with ions formed from impurities or by chemical decomposition of the dielectric, may allow the gradual accumulation of positive space charges in the vicinity of the anode. This also may increase the local field sufficiently to start breakdown. It may be avoided with gaseous dielectrics or with liquids, if circulation is maintained because under such conditions the piling up of ions in one place is more difficult. The emphasis on pure materials that have low dielectric losses and negligible conductivity, as well as the cooling of the dielectric whenever possible, is well placed.

It is possible to calculate the height of the energy barrier and thus estimate the intrinsic breakdown strength of ionic materials by using the formulas developed by Seeger and Teller and by Fröhlich. Application of this sort of mathematical treatment has been applied, although with much greater difficulty, to a few pure organic insulating materials. For example, calculations applied to hydrocarbon chains indicate that the breakdown strength should increase with chain length, but that, within the experimental uncertainty that holds, all hydrocarbons should be roughly of the same order. Experimentally, values range from about 4.5×10^6 volts per centimeter for ordinary paraffin wax to about 7×10^6 volts per centimeter for polythene. It also has been observed that the dielectric strength of polystyrene increases with the degree of polymerization.

It is questionable whether it will be possible by the use of these formulas to find new dielectric materials with any very large increase in intrinsic dielectric strength. It should, however, be possible to make predictions from the formulas as to the relative intrinsic breakdown strength of materials more or less closely related chemically, but other factors may be of more importance in determining whether breakdown will occur under a given set of circumstances.

The phenomenon of cumulative impact ionization and electron avalanche generally proceeds to dielectric failure in liquid and solid dielectrics, unless some mechanism is available to stop it. It previously was observed that certain gases, such as the Freons containing a large proportion of halogen, showed high breakdown strengths. The reason for this was attributed to the ability of halogen atoms to remove electrons from the path of the discharge by the formation of halide ions, which are relatively slow moving and difficult to break up again. Although this results in an effective increase in the energy needed by the electrons to cause cumulative ionization, it also may be a factor in breaking up or suppressing electron avalanches. It appears from a survey of the available data that such an effect can be observed in liquids—for example, the breakdown strength of symmetrical halogen-containing organic liquids (those with low or zero dipole moment) is somewhat higher than that of the parent hydrocarbons.

Little has been suggested to raise the breakdown strength of liquids and solids by preventing the growth of the positive space charge. The slow accumulation of field-distorting space charges in liquids at voltages below the breakdown voltage can be avoided by circulating the dielectric.

CORONA

The phenomenon of corona can be observed in a dielectric when the impressed field is sufficiently divergent. Under this condition, local breakdown can occur in the neighborhood of the electrodes but, because of the divergence of the field, conditions beyond a certain distance from the electrodes are not favorable for maintaining the discharge. Thus, corona is usually confined to the vicinity of the electrodes. In dielectric testing, corona may precede the actual breakdown discharge as the voltage is raised, if the electrode configuration is favorable.

IMPULSE BREAKDOWN

It is a widely held opinion that the impulse strength of an insulating material—that is, the breakdown strength under a rapidly applied voltage stress—may be considerably different from the static dielectric strength obtained with slowly applied voltages. When considering the relation between time lag and applied voltage as outlined previously, we would expect to measure higher voltages for impulse-strength tests than for static-breakdown tests as a necessary consequence of the small but finite time required for complete breakdown to occur. As shown in Fig. 3, the magnitude of the overvoltage will depend on the applied voltage, as well as a time-lag characteristic of the material being tested. In addition, dielectric losses and conductivity in insulating materials may exert an effect in lowering the observed breakdown strength in static tests, whereas under impulse conditions these factors may not be operative.

Much of the impulse-test data on insulating liquids has been taken under conditions where point electrodes have been employed. The space-charge phenomena in the neighborhood of sharp points, although not affecting the mechanism of the breakdown, may present secondary effects that are hard to interpret. For example, in breakdown tests with point electrodes, we would expect that for relatively large electrode separations the breakdown strength would not continue to increase linearly with distance, as is observed at small separations.

It also has been observed that symmetrical molecules have higher breakdown strengths under impulse than unsymmetrical molecules of similar chemical composition. Some workers have indicated that perhaps this symmetry effect is due to rupture of the liquid dielectric by the sudden torque effect of the field on unsymmetrical molecules. Considering the actual voltage that one molecule sees in a field sufficient to cause breakdown (about a tenth of a volt), and the fact that the energy imparted to the molecule by the field is usually smaller than the thermal energy by orders of magnitude, such a conclusion is questionable. The electronic breakdown mechanism presumably would be very much more rapid a process than liquid shear in fields of this strength. However, it is true that, under impulse-test conditions, local fields in the neighborhood of point electrodes might become strong enough to exert an appreciable effect on the orientation of the molecules and thus affect the field distribution to favor breakdown.

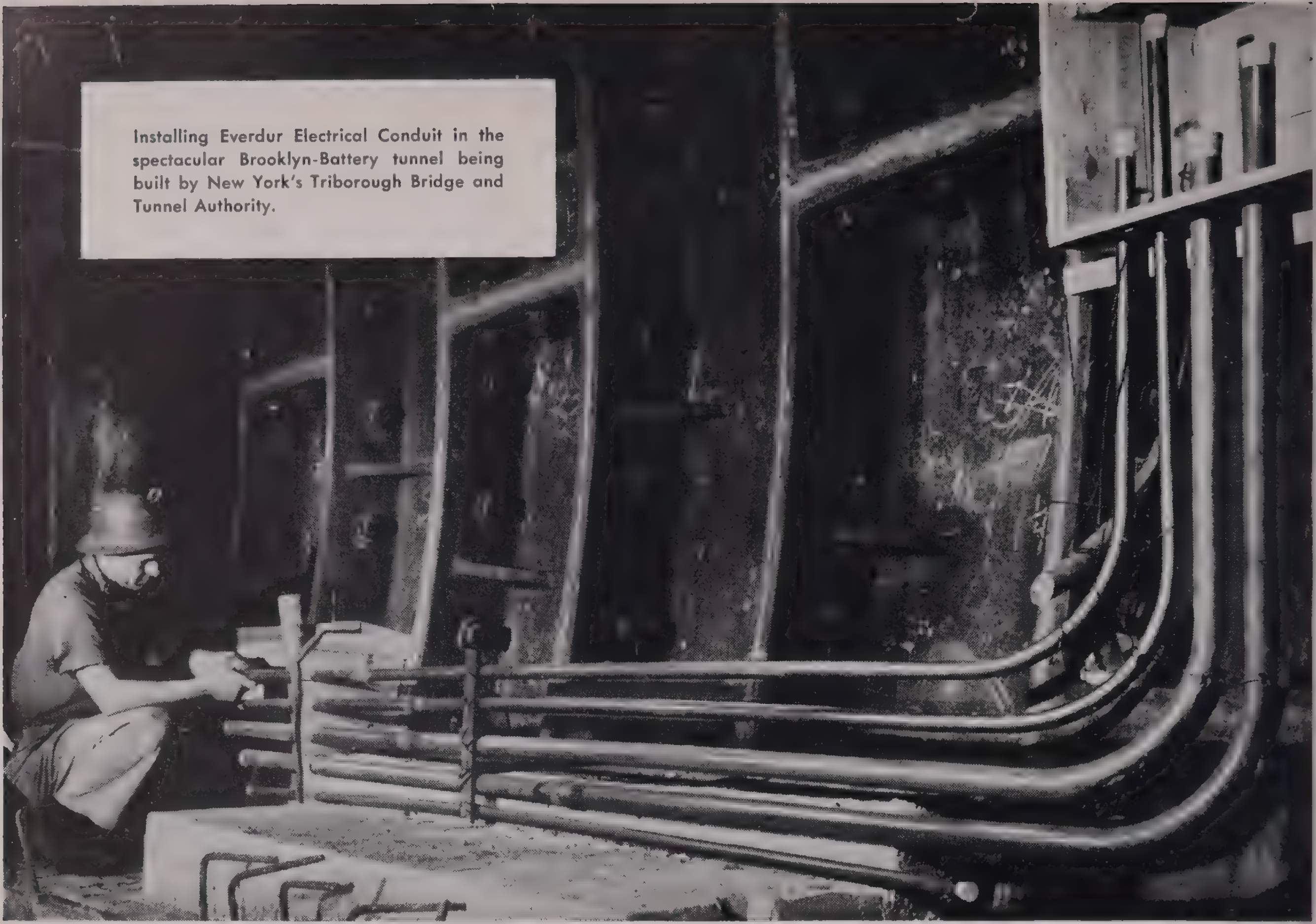
Failure of solids to withstand the mechanical stress associated with the field can happen under unusual circumstances—for example, with needlepoint electrodes, or where a small part of the dielectric has to support the field between large electrodes. This applies particularly to plastics with low yield stress.

RETROSPECT

This has been a rather simple presentation of the electronic nature of the breakdown of gases, liquids, and solids under electrical stress. The breakdown mechanism itself, however, is far from simple, and its elucidation represents a great deal of work on the part of a large number of capable scientists and engineers. There is much evidence to support the universality of this mechanism, and there remains very little in connection with dielectric breakdown phenomena that cannot be explained with the aid of the mechanism. However, by the very nature of the breakdown process, we must expect some degree of uncertainty and unpredictability in the way dielectrics behave under high voltages. Although occasionally a few factors show why one dielectric stands up under higher voltages than another, there is still much to be learned about the effect of minor variables on the breakdown strength of conventional insulating materials, particularly in regard to conditions prior to breakdown which may lead to dielectric failure.

Notes and References

(1) The term "breakdown" as used here refers to a complete puncture of the dielectric and the passage of an appreciable current.
(2) Loeb: *Fundamental Processes of Electrical Discharge in Gases*, John Wiley and Sons, New York, 1937.
(3) Theoretically, the lowest voltage at which breakdown will occur for a pure material under perfect test conditions. This also may be referred to as "intrinsic breakdown strength." In practice, many factors will operate to give actual breakdown voltages above or below this figure.
(4) Not to be confused with the primary ionization processes by which a gas molecule is split into free electrons and a positive ion by collision with an electron.
(5) A. von Hippel, *Jour. Applied Physics 8*, 815, 1937.
(6) Seeger and Teller, *Phys. Rev. 54*, 515, 1938; *58*, 279, 1940.
(7) H. Fröhlich: *Reports on Progress in Physics*, vol 6, 411, The Physical Society, London, 1939; *Nature 151*, 339, 1943.
(8) S. S. Attwood and W. H. Bixby, *Jour. Franklin Inst. 235*, 259, 1943.



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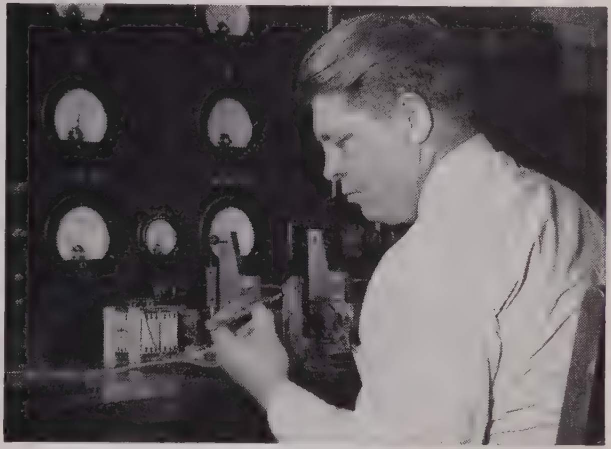

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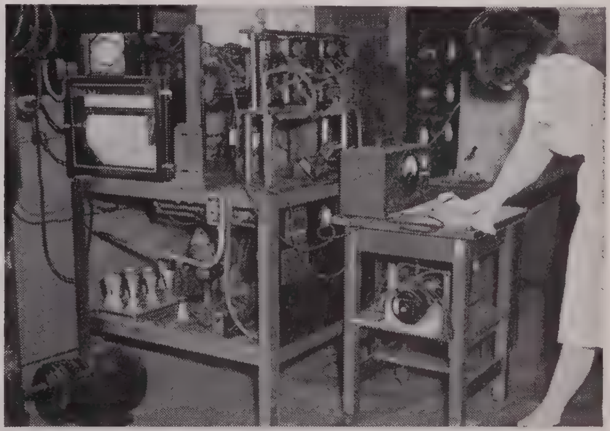

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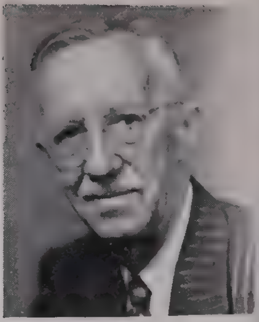
CABLE TERMINATION FOR TRANSFORMERS AND TRANSFORMER DISCONNECTING SWITCHES



Palme

The problem of making electrical connection quickly and reliably to power-handling apparatus involves careful consideration of the design of the terminating equipment

By A. PALME
Power Transformer Engineering Division
General Electric Company

TRANSFORMERS are frequently connected to their power supply by means of underground cables which enter the transformer either directly or through a transformer disconnecting switch. Sometimes more than one transformer is connected to the feeding cable. In this case, the cable enters the first unit, is carried out again to the next unit, and so on, in an arrangement called "loop feed."

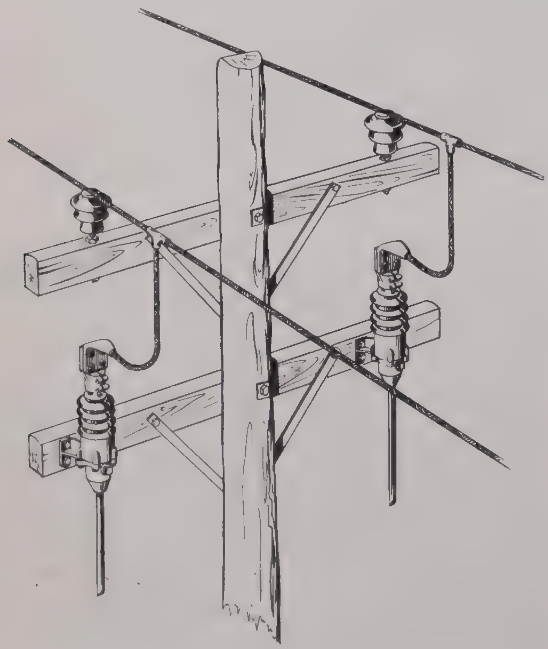


Fig. 1. Conventional use of standard pothead

When the transformers are large and installed outdoors, the cables, as a rule, are buried underground and enter the units from below. Smaller transformers, especially those installed indoors, may sometimes be fed from overhead cable runs, in which case the cable or the cables enter the transformer from above.

In all of these applications the problem of determining the best way of terminating the cable has to be faced. So-called potheads have been used for a long time, and most operating companies are thoroughly familiar with the highly skilled job of making reliable pothead terminations of single- and multiple-conductor high-voltage cables. It has thus become a matter of course or habit to call for a pothead whenever and wherever a cable termination has to be made and to take it for granted that an experienced group of men will be available to install it.

The inherent difficulties in applying the conventional pothead to transformers and switches led to the designing of an improved termination, called a terminal chamber, in which all of the disadvantages of the commercial pothead are avoided, thus making installation a matter of great simplicity. A great many such cable terminations have been in faultless operation for a number of years.

POTHEADS

The original use of potheads was to provide a convenient and electrically safe termination of a cable *in air*. In other words, a pothead was installed where the underground cable comes above ground, and the line continues as an open, overhead line (FIG. 1). Under these circumstances, the installation of a pothead was relatively simple, and the replacement of a damaged pothead was equally simple.

A different problem has to be faced if the cable enters a transformer, or a disconnecting switch attached to it. Both the transformer and the switch are oil-filled devices, so that the cable does not terminate in the air but in oil. All potheads are weatherproof and watertight, so that no difficulty would be experienced by mounting them in an oil-filled vessel. It would no longer be necessary to provide rain-shedding petticoats on the porcelains; a plain corrugated porcelain would be satisfactory. Since the flash-over of an insulator is much lower in air than under oil, a shorter length of the outside porcelain would be adequate. Likewise, the distance between live parts can be reduced. All told, for a given voltage, a smaller-size pothead can be used under oil than in air. In some pothead constructions, this air-oil voltage ratio may be as high as 1:2.

When it comes to the installation of a pothead to an oil-filled vessel, however, conditions are no longer as simple as they were in air. For one thing, the location of the pothead is now very definite. A plus of ½ in.

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or less may cause a bowed-out and therefore unsightly cable run. A minus of ½ in. or less may make the installation impossible, since the cable cannot be stretched. A very exact cutting of the cable to correct length will be essential. It must be remembered that the actual end connection between the cable conductor and the pothead terminal is made inside, near the end of the pothead porcelain (Fig. 2). A certain amount of bending will therefore be required to make a good, neat job of installation. If, on the other hand, the pothead has to be replaced, or if the transformer has to be moved away without cutting the cable off below the pothead, the disassembly will require the draining of the oil in the vessel, the removal of the pothead terminals, and the removal of the whole pothead, which again will mean considerable bending of the cable.

The mechanical characteristics of the potheads must likewise be considered, because there is the question of whether the conventional types of potheads have adequate mechanical sturdiness for all applications to which they may be put.

When designing transformer disconnecting switches, it is very tempting (from space- and cost-saving viewpoints) to arrange the contacts, into which the switch knives engage, directly on the pothead terminals. Since the operation of such a switch consists of a fairly rapid motion, and since the knife blades or the collector of the switch have to overcome a sizeable contact pressure, the pothead bushings have to stand up under considerable mechanical stresses. To make conditions still worse, many three-phase potheads have their porcelain bushings "fanned-out" (as shown in Fig. 2), so that the pressure upon the two outer bushings entails a bending moment applied to the porcelains. Entering a cable into a disconnecting oil box through a pothead will therefore always call for the switch contacts to be mounted on separate porcelain posts, which are designed and dimensioned for such mechanical stresses as may have to be encountered. Fig. 3 shows the use of a conventional pothead in this manner and also how the previously mentioned difficulties of making the pothead installation and allowing for the removal of the transformer have been lessened by having the pothead enter a removable front section of the switch box.

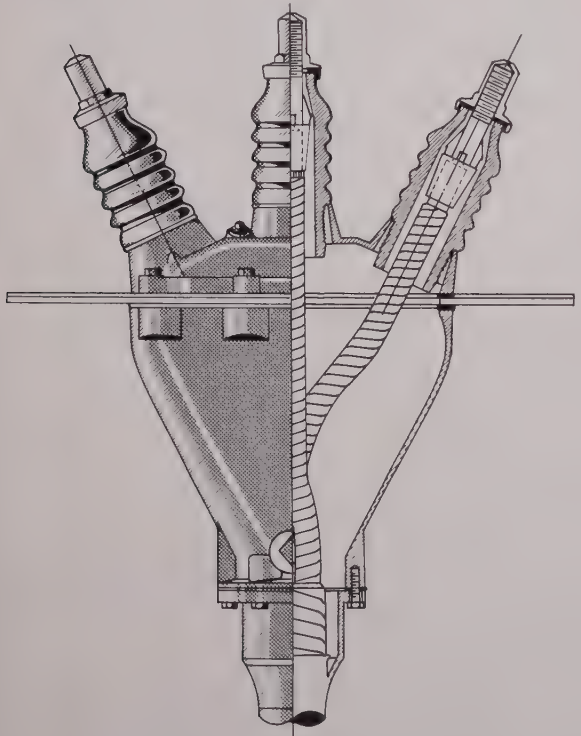

Fig. 2. Detail and sectional view of standard pothead

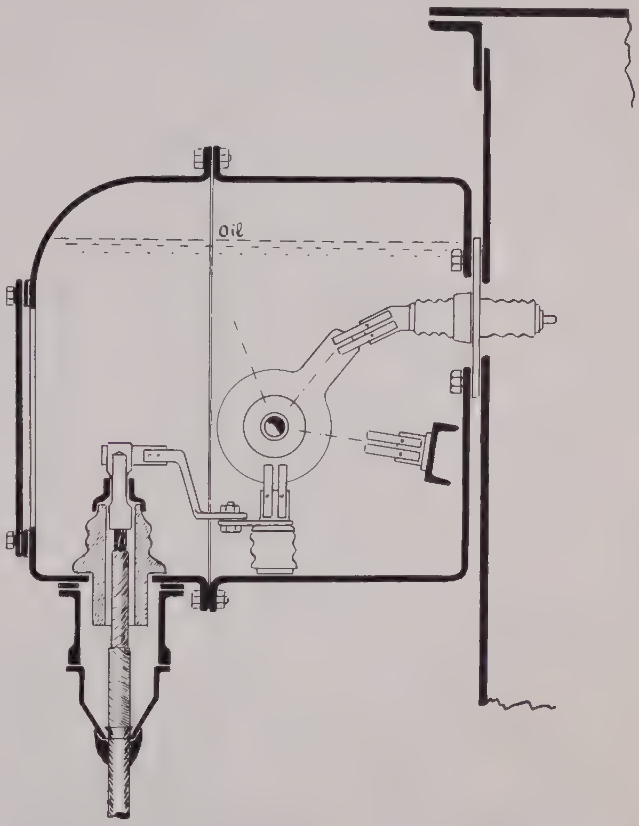

Fig. 3. Use of conventional pothead for cable termination into an oil-filled transformer disconnecting switch

It will be understood readily that, for loop-feed-type switches, two separate potheads will have to be installed on the switch to terminate the two cables required.

Terminal Chambers

Quite a number of years ago, General Electric developed a new style of cable termination, particularly suited for connecting a transformer or its disconnecting switch to the feeder cable. This termination combined all of the desirable electrical features of commercial potheads with superior mechanical features, and at the same time simplified its installation.

Essentially, the upper part of the pothead with its porcelain bushings has been divorced from the lower or body part of the pothead, and has been made part of the transformer or switch. Three sturdy porcelain bushings, designed, dimensioned, and spaced for oil immersion, are mounted oil-tightly into the bottom (or the top, for top feed) of the switch box and each bushing has copper studs rated up to 400 amp carrying capacity. A rectangular, top-flanged, sheet-steel box can be bolted to the underside of the switch box, and corresponds to the body of a pothead. To the underside of this sheet-steel box can be fastened any of the customary pothead fittings such as a wipe sleeve, a stuffing box, a conduit coupling, a multiple cable entrance, etc. If the cable is a three-conductor cable, a single cable entrance is used. If there are three single-conductor cables coming in, either three single entrances or one multiple entrance for all three can be used. For lead-covered cables, a wipe sleeve makes the simplest type of sealed entrance. In this case, the sheet-steel box underneath the switch box has solid sides. If a stuffing-box entrance of the cable or cables is preferred, or if the cable is not lead-covered, the sheet-steel box has a removable-front handhole to aid in installing this fitting. Fig. 4 shows the section (side view) through a disconnecting switch with cable termination, as described. This is known as a "Terminal Chamber," and at present is made for voltages up to 15,000. After the necessary electrical connections have been made between the cable conductors and the lower ends of the switch bushings, all live parts are covered with standard cable taping. The sheet-steel box is then raised to its ultimate location, is bolted with its gasketed flange to a corresponding flange on the underside of the switch box, and is filled with a suitable cable compound. A filling plug below and an air-vent plug above facilitate the filling operation.

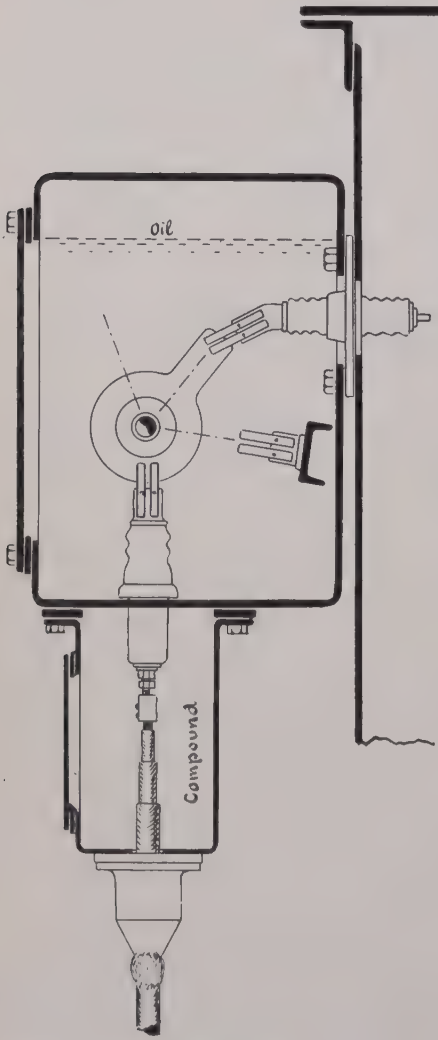

Fig. 4. Cable termination with a terminal chamber underneath an oil-filled transformer disconnecting switch

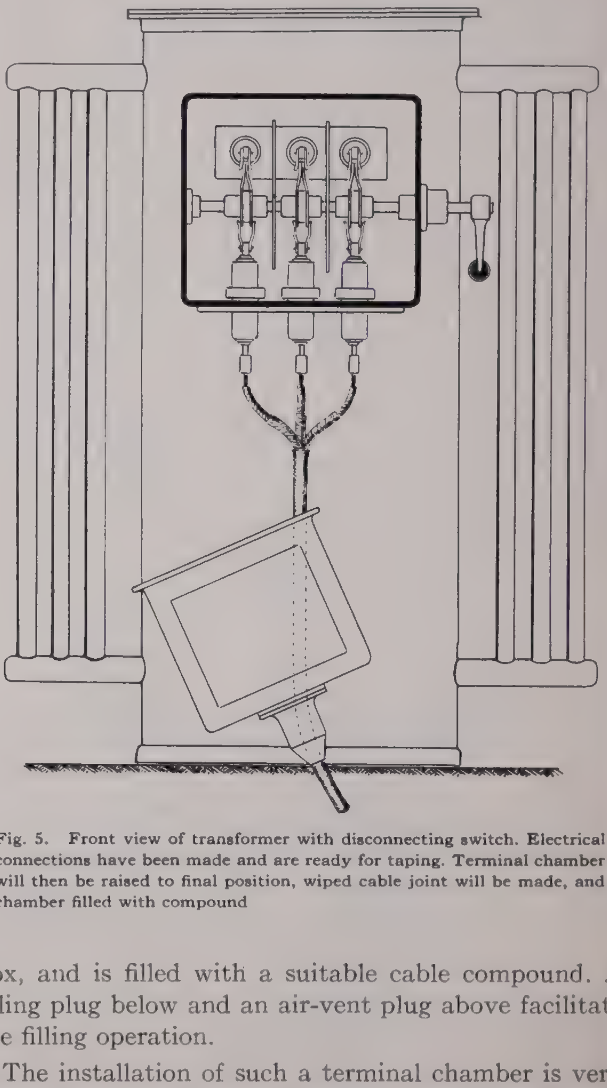

Fig. 5. Front view of transformer with disconnecting switch. Electrical connections have been made and are ready for taping. Terminal chamber will then be raised to final position, wiped cable joint will be made, and chamber filled with compound

The installation of such a terminal chamber is very simple; all joints are made with the sheet-steel casing lowered or are readily accessible through the front opening (Fig. 5). No bending of the cable is required. Removal of the transformer is equally simple and requires no draining of oil. If a loop-feed arrangement is called for, the sheet-steel box is made slightly wider, and holds two wipe sleeves at the bottom for the incoming and the outgoing cable. The loop connection itself is made directly on the copper terminals of the porcelain bushings (Fig. 6).

Experience with hundreds of terminal-chamber installations has been excellent. Cable crews, called upon to make connections to transformers or to disconnecting switches, are convinced that this type of cable termination has considerable advantage over the use of the usual potheads.

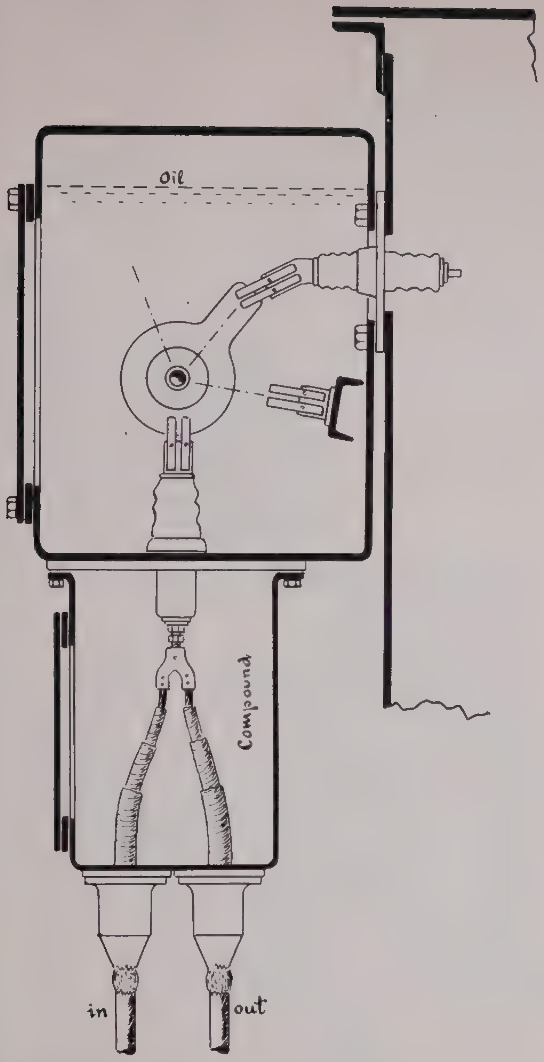

Fig. 6. Terminal chamber for loop-feed arrangement on a transformer disconnecting switch

CONCLUSION

The following is a summary of the comparative features of potheads and terminal chambers, assuming both are electrically equal:

Pothead	*Terminal Chamber*
Made primarily for air installation.	Made only for oil installation.
Porcelain bushings provide electrical safety but are not intended to take mechanical stresses.	Porcelain bushings are part of the oil-filled vessel, are always mounted vertically, and are mechanically very strong.
Correct and neat installation requires skilled cable crew.	Correct installation requires no special skill.
Installation requires more or less severe bending of cable.	Installation requires no bending of the cable.
Possibility of an outside oil leak from switch box.	No possibility of an outside oil leak.
Removal of transformer without cutting of cable calls for oil drainage and partial disassembly of pothead.	Removal of transformer without cutting of cable entails no oil handling and is relatively simple.
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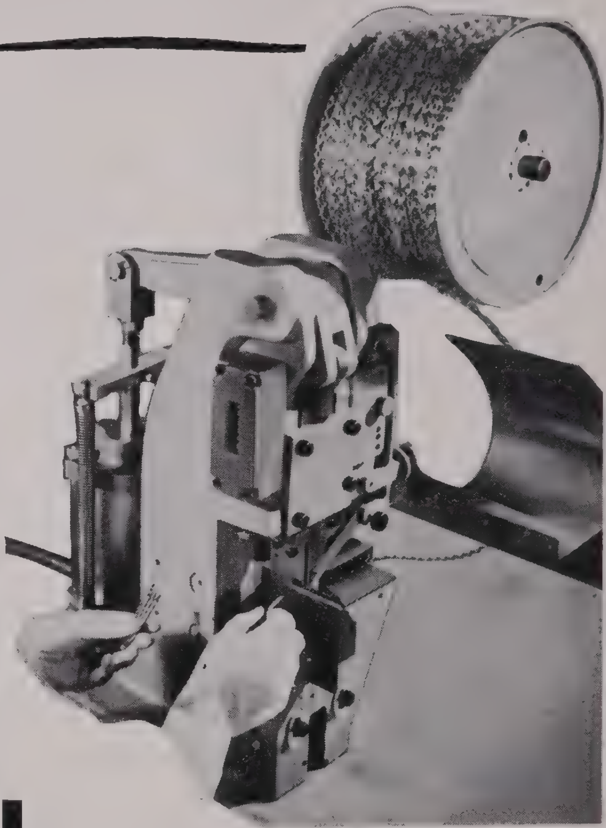

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PROTECTIVE ATMOSPHERES IN INDUSTRY . . Part II

Theoretical considerations involving chemical reactions occurring in the principal types of gases commonly used as furnace atmospheres

By A. G. HOTCHKISS and H. M. WEBBER
Industrial Heating Divisions, General Electric Company

TO obtain a basic understanding of gas atmospheres, it is essential to be familiar with some of the chemical reactions between the gases and the materials with which they are in contact at elevated temperatures. In this article consideration will be given only to protective furnace atmospheres used in the treatment of metals.

There are seven principal gases which are most commonly found in furnace atmospheres. These seven gases are listed in Table III, each followed by its chemical symbol which will be used throughout this discussion. In an attempt to convey a brief and direct outline of the problem, the table includes a word picture of the reactions of each gas with iron, iron oxide, or iron carbide; also results of the reactions. The text elaborates upon these reactions as well as others; and, unlike the table, it is not confined entirely to ferrous metals.

The simplest protective atmosphere for heat treating metals is a pure inert gas—for iron or steel, such a gas is argon. Argon does not react with the surface of the metal to form a scale; it does not dissolve in the metal; nor does it react on a smooth surface to cause roughening. Argon, however, is not practical because of high cost and the fact that it cannot be maintained with the required purity in a commercial furnace.

Nitrogen, because it is inert, is another good prospect; but, in spite of its ready availability, nitrogen is not a suitable atmosphere in general because it too lacks self protection against impurities such as oxygen, carbon dioxide, and water vapor. Very small traces of these gases will allow oxidation and decarburization of steel being treated in nitrogen.

To prevent oxidation, the normal furnace atmosphere should be oxygen-free. However, since the percentage (partial pressure) of oxygen is always much greater in the surrounding air than in the furnace, the oxygen tends to enter the furnace. In the annealing of steel strip, a large stack of coils is commonly placed on the furnace base and covered with a gas-tight metal retort as shown on the COVER. Assume that this retort is sealed at the base by several inches of sand. Before the heating furnace is placed over this retort, the air is completely purged out with a suitable protective atmosphere. If the flow of this atmosphere is then stopped, the infiltration of air back through the sand seal and into the inside of the retort will start immediately. It is necessary to maintain a very definite positive flow of atmosphere from inside toward the outside of the seal to prevent any appreciable infiltration. Even with a positive liquid seal of water or oil, as shown on the COVER, small amounts of oxygen may be given off from the surface of the seal inside the retort, which would be sufficient to contaminate an atmosphere of pure inert gas.

If the protective atmosphere is pure nitrogen, it cannot neutralize any oxygen, whether in the form of free oxygen, carbon dioxide, or water vapor which might find its way into the furnace, as would otherwise be true if another gas (such as hydrogen or carbon monoxide) capable of reacting with and neutralizing the undesirable oxygen were present. In principle, therefore, it is advantageous to use not a pure inert gas but a suitable gas mixture such as nitrogen plus hydrogen, or nitrogen plus carbon monoxide, in sufficient quantities to consume the oxygen and to neutralize the oxidizing effect of the product thus formed.

COMBUSTION REACTION

The simplest gas reactions thus taking place would be the combustion reaction between the hydrogen or the carbon monoxide and the oxygen present, according to the following chemical equations:

$$2H_2+O_2=2H_2O \qquad (1)$$

$$2CO+O_2=2CO_2 \qquad (2)$$

The combustion reactions are also mainly involved in the producing of furnace atmospheres by totally or partially burning fuel gases. For this process, the combustion of hydrocarbon gases, such as natural gas (methane CH_4), would be as follows:

$$CH_4+\text{air}(2O_2+8N_2)=CO_2+2H_2O+8N_2 \qquad (3)$$

Typical equipment for producing combusted-gas furnace atmospheres by this method is shown in FIG. 7. It employs a premix system supplying the fuel gas and air mixture under pressure to the burner on the right which fires into the end of a closed cylindrical combustion chamber at the top. This equipment and its application will be completely described in a succeeding part of this serial.

DISSOCIATION REACTION

When furnace atmospheres are under consideration, dissociation reactions are frequently encountered which result in the changing of a simple gaseous compound into a physical mixture of two or more simple gases.

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This is well illustrated by the dissociation of anhydrous ammonia at high temperature, according to the equation

$$2NH_3+\text{heat}=N_2+3H_2 \qquad (4)$$

This means that two volumes of ammonia vapor dissociate into a mixture of one volume of nitrogen, plus three volumes of hydrogen, or a mixture which is 25 percent nitrogen and 75 percent hydrogen by volume. FIG. 8 illustrates a typical ammonia dissociator. This equipment and the use of gas produced by it will be fully explained in a later part of this serial.

Hydrocarbon gases may be introduced into any furnace atmosphere by the volatilization of oil on the work, such as rolling oil on steel strip and lubricants on stamped metal parts. Hydrocarbon gases can be introduced purposely into the furnace as in the gas-carburizing process (which will be discussed later), to furnish a form of carbon that will be absorbed by the surface of the steel.

Such breaking down or dissociation is illustrated in the following reactions:

$$CH_4\ (\text{methane})+\text{heat}=2H_2+C \qquad (5)$$

$$C_3H_8(\text{propane})+\text{heat}=4H_2+3C \qquad (6)$$

The degree of dissociation of methane with temperature is shown in FIG. 9, which illustrates the equilibrium between the cracked and uncracked gases existing at any given temperature. This means that at an annealing temperature of, say, 1500 F an atmosphere containing an excess of methane would be expected to crack or dissociate until about 4.5 percent methane remains, and at about this point the reaction would cease.

OXIDIZING REACTION

The most common and important result to be obtained from protective atmospheres is the prevention of oxidation of the surfaces of the materials being treated. Oxygen, either in the free state such as in air, or in combination as in carbon dioxide and/or water vapor, is the most common cause of the oxidation it is desirable to prevent.

The following reactions are typical of the results of free oxygen in contact with iron at elevated temperatures:

$$O_2+2Fe=2FeO \qquad (7)$$

$$O_2+4FeO=2Fe_2O_3 \qquad (8)$$

These reactions may represent an oxide ranging from a deep blue discoloration to a loose oxide scale.

A similar reaction of oxygen with copper also takes place.

Carbon dioxide does not react with copper, but reacts with iron according to the following equations:

$$CO_2+Fe=CO+FeO \qquad (9)$$

$$CO_2+3FeO=Fe_3O_4+CO \qquad (10)$$

Reactions (9) and (10) are to be considered as reversible, to a point of equilibrium where the value of the carbon monoxide produced will counterbalance the value of the carbon dioxide in accordance with fixed equilibrium data at definite temperatures.

The subject of chemical equilibrium and equilibrium constants is a study within itself. Detailed information on these matters are given in standard texts on physical chemistry and in published technical literature(1)(2)(3). However, an understanding of its meaning is necessary to grasp the fundamentals of protective atmospheres.

Consider this simple illustration: Experiment shows that, if iron and iron oxide are heated in a closed vessel at constant temperature in contact with any mixture of carbon monoxide and carbon dioxide, the composition of the gas changes until a certain definite composition, characteristic of that temperature, is attained. Thus, whatever the initial composition of the gas, the final composition is the same, as long as both solid phases (iron and iron oxide) remain present. For example, at 1832 F, the final composition is 72 percent carbon monoxide and 28 percent carbon dioxide, regardless of whether the gas has more or less carbon monoxide at the beginning; a mixture of this composition is, therefore, in equilibrium with iron and iron oxide at 1832 F. Moreover, at this temperature, any mixture which contains more than 72 percent carbon monoxide tends to approach this composition by reduction of iron oxide, whereas a mixture which contains less than 72 percent tends to oxidize iron.

A knowledge of the equilibrium composition of the gas as a function of temperature permits us to predict the way in which any mixture containing carbon monoxide and carbon dioxide tends to react with iron or iron oxide at any temperature. Whether reaction does occur depends on a great many different factors but, in general, the rate of reaction is fairly high at high temperatures. It is usually safe to assume that oxidation, or reduction, does occur at heat-treating temperatures if the composition of the gas is favorable.

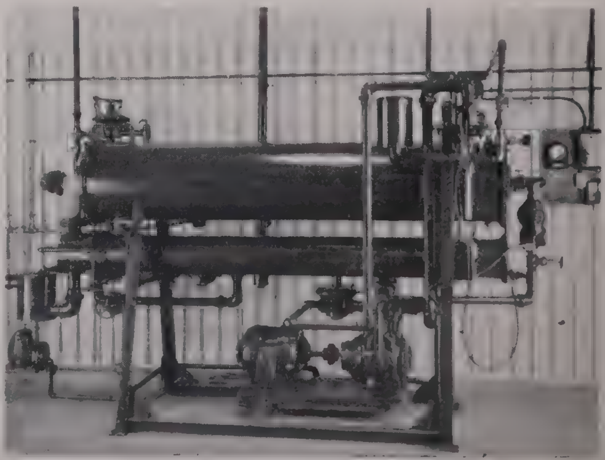

Fig. 7. A 4000-cfh atmosphere gas converter for producing combusted-gas atmospheres by partially burning fuel gas with air

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(1) Numbered references are listed at the end of this Part.

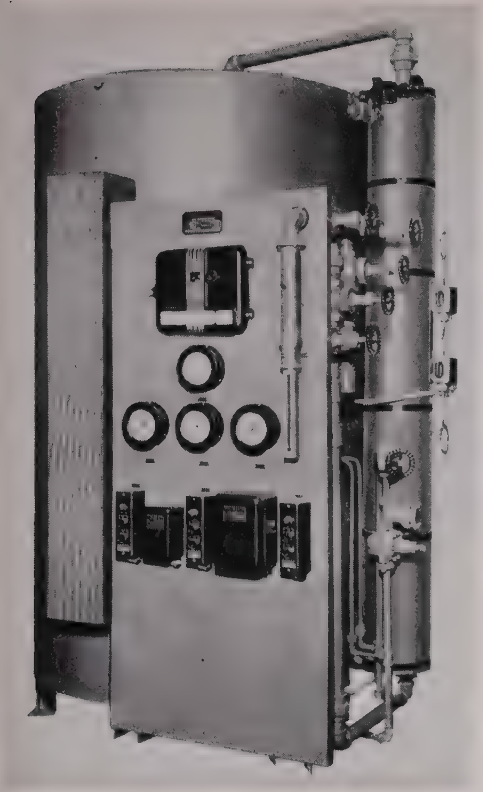


Fig. 8. An ammonia dissociator complete with control panel for producing 2000 cfh of dissociated ammonia gas from liquid ammonia

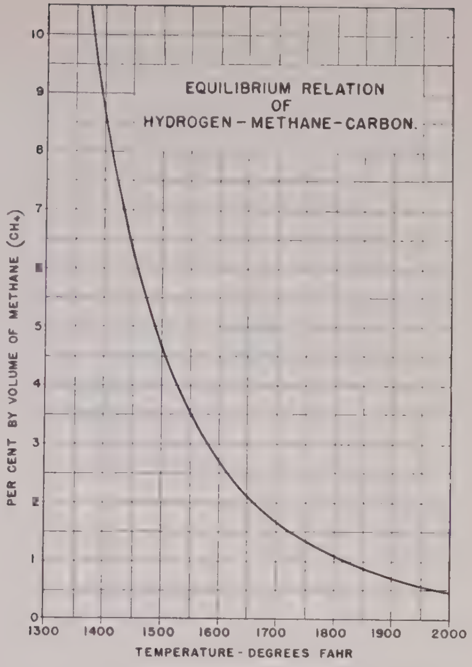


Fig. 9. Equilibrium relation of hydrogen, methane, and carbon in gas at various temperatures

Equilibrium data of this sort are expressed in terms of ratios of the gases which equal a constant, and which constant has a definite value for each temperature. With this information, it has been possible to set up theoretical equilibrium curves, such as those in Fig. 10. By referring to the righthand curve which gives the equilibrium relations between iron, iron oxide, carbon monoxide, and carbon dioxide it can be noted that the area to the right of the curve is in the oxidizing range, and the area to the left is in the reducing range.

If an atmosphere then contains equal amounts of CO and CO_2, it should be possible to heat clean iron in this atmosphere to a temperature of approximately 1000 F without any blueing or discoloration taking place. However, if the temperature is increased to 1100 F, the plot falls on the oxidizing side of the curve and oxidation would be expected to take place.

The remaining important oxidizing reaction is that of water vapor with iron according to the following equations:

$$H_2O + Fe = H_2 + FeO \qquad (11)$$

$$H_2O + 3FeO = H_2 + Fe_3O_4 \qquad (12)$$

This reaction also has its equilibrium values which are plotted in Fig. 10 (as shown in the lefthand curve). Again, the area to the left of the curve indicates a reducing reaction, while that to the right of the curve indicates oxidation.

The oxidizing action on steel below 600 F is too slow to be a matter of concern in commercial heat-treating practice. It can be seen from the curves, therefore, that a gas containing 5 percent H_2O and 95 percent H_2, with a ratio of H_2O/H_2 of about 0.05 and represented by the ordinate *a-a′*, will not oxidize bright steel at any temperature, and in that sense is neutral to bright steel. In fact, any iron oxide on it would tend to be reduced[(4)].

Assume, however, a gas containing 3.7 percent water vapor and 15 percent hydrogen, or a ratio of 0.25, and a gas temperature of 1200 F. This point plots at *b′* and is well within the reducing range. However, when the temperature drops to 975 F on *b′-b*, the plotted point crosses the theoretical equilibrium curve and enters the oxidizing range. It would, therefore, be impossible to slow-cool steel in such an atmosphere without oxidation taking place.

If, however, we have a complex gas containing also CO and CO_2, such as obtained from the partial com-

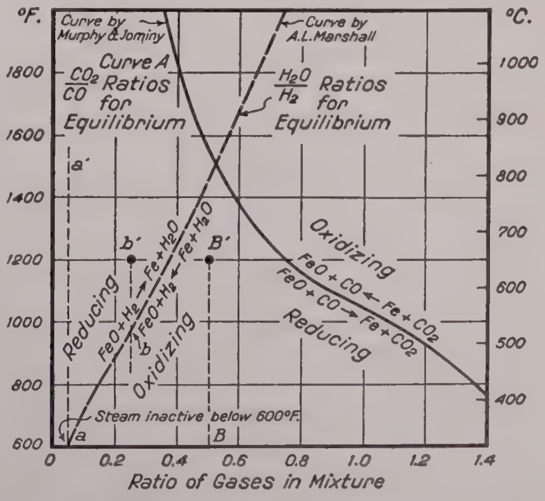


Fig. 10. Theoretical equilibrium relations between iron and iron oxide when in contact with hydrogen and water vapor or carbon monoxide and carbon dioxide at heat-treating temperatures

bustion of hydrocarbon gases, the situation changes. The theoretical equilibrium curve for iron, iron oxide, CO, and CO_2 has the opposite slope, crossing that of iron, iron oxide, H_2O, and H_2 at about 1500 F. Therefore, if we have, say, 5 percent CO_2 and 10 percent CO in the above gas, along with the hydrogen and water vapor, the ratio of the carbon gases (CO_2/CO), which is 0.50 and plotted at B' (1200 F), shows the mixture to be quite strongly reducing and increasingly so as the temperature decreases. It is possible, therefore, with the complex gas to cool steel down through its critical range below 1000 F without oxidation, because the reducing effect of the equilibrium of CO_2 divided by CO overcomes the oxidizing effect of the combination of H_2O divided by H_2.

WATER-GAS REACTION

The equation

$$CO+H_2O=CO_2+H_2 \qquad (13)$$

is known as the water-gas reaction. The equilibrium data for this reaction do not give directly any information as to whether a gas mixture containing these constituents is oxidizing or reducing to iron and iron oxides. This information is supplied by data from the oxidation-reduction reaction previously considered. Reaction (13) is readily reversible and is important because it is the reaction by which most controlled atmospheres adjust themselves to furnace conditions. When using an atmosphere containing the four gases involved in this reaction, it is necessary to consider its composition within the furnace at furnace temperature.

The equilibrium for this reaction is based on the equation

$$\frac{CO\times H_2O}{CO_2\times H_2}=\text{constant } K \qquad (13a)$$

in which the percentages of the constituents are substituted for the symbols, leaving a numerical fraction which can be reduced. This constant has certain definite values, depending on the temperature to which the gases are heated. (Austin and Day give complete tables of the value of K).$^{(1)}$

Table III

GASES COMMONLY FOUND IN PROTECTIVE FURNACE ATMOSPHERES AND THEIR REACTIONS WITH IRON AND IRON CARBIDE

Gases	Symbols	Customary Percentages (In Furnace) For No Oxidation	REACTIONS			Customary Percentages (In Furnace) For No Decarburization	Remarks
			The Gas Combines With	To Form	Reaction		
Nitrogen	N_2	Up to 100			Neutral	Up to 100	Inert diluent present in most atmospheres. Seldom can be maintained sufficiently pure when used alone.
Oxygen	O_2	0.0	Iron	Iron Oxide	Strongly oxidizing		Must be eliminated to prevent oxidation and decarburization.
			Iron Carbide	Iron	Strongly decarburizing	0.0	
Carbon Dioxide	CO_2	5 or less	Iron	Iron Oxide	Strongly oxidizing		Allowable amount depends on amount of CO present.
			Iron Carbide	Iron	Strongly decarburizing	0.0	Must be eliminated to prevent decarburization.
Water Vapor	H_2O	3 (Dewpoint +75 F or less)	Iron	Iron Oxide	Oxidizing		Allowable amount depends on amount of H_2 present.
			Iron Carbide	Iron	Strongly decarburizing	Below 0.25 (Dewpoint +12F)	Small amounts of H_2O may be compensated for by CO and CH_4.
Hydrogen	H_2	2 to 100	Iron Oxide	Iron	Strongly reducing	2 to 100	Low values for long cycle heat-treatment only. Normally 12 percent or more for short cycle treatments.
Carbon Monoxide	CO		Iron	Iron Carbide	Slightly carburizing	2 to 20	Desirable gas for preventing decarburization.
		8 to 20	Iron Oxide	Iron	Reducing		Desirable gas for preventing oxidation in low-temp. ranges. Neutralizes effect of CO_2.
Methane	CH_4		Iron	Iron Carbide	Strongly carburizing	1.5	Generally desirable in small quantities to neutralize decarburizing effect of atmosphere contamination by CO_2 and H_2O.
		1.5	Iron Oxide	Iron	Reducing		

It is easy to determine from this reaction that any gas containing CO, CO_2, and H_2, even though perfectly dry when entering a furnace, would, when heated to furnace temperature, very quickly produce sufficient H_2O to come to equilibrium conditions for that particular furnace temperature. If both the CO_2 and the H_2O are removed, a fairly stable condition will then exist.

As an example of this reaction, an open brickwork box-type electric furnace, operated at 2000 F, was thoroughly purged with a low-ratio combusted gas containing 11 percent CO, 16 percent H_2, 4 percent CO_2, but dried so that the moisture content was only 0.018 percent (−40 F dew point). After sufficient time to get completely stable conditions within the furnace, however, the dew point of a sample from the chamber was +45 F. At this time, and without interrupting the flow of gas to the furnace, the CO_2 was reduced to zero, all other conditions remaining the same. Two hours after the CO_2 had been reduced to zero, the dew point as measured from a sample taken from within the furnace chamber had dropped to +20 F. Then the CO_2 was again introduced into the gas, and in a few hours the dew point had increased to give a reading of +47 F.

ETCHING

The water-gas reaction must also be considered with respect to etching or roughening of the surface of bright steels, which will occur in the higher temperature ranges of long annealing cycles.

Marshall(5) found that this could be explained by the combination of two reactions, the first being the water-gas reaction (13), and the second being the producer-gas reaction:

$$2CO = CO_2 + C \qquad (14)$$

Etching will result if the gas mixture is too high in CO and too low in water vapor—that is, if the proportions are too far from equilibrium in relation to the amount of CO_2 and H_2 in the mixture. In other words, a small amount of water vapor is required in these complex mixtures, to secure equilibrium of the component gases with each other, when at high temperatures. If water vapor is not present in sufficient quantity for equilibrium, the component gases will tend to dissociate and recombine to establish equilibrium, the necessary water vapor for equilibrium being formed as a product. The steel acts as a catalyst for the reaction and its surface becomes roughened in the process. Marshall checked these reactions by actual tests, working with bright steel at a temperature range of 1200 F. He reported as follows:

"Experiment has shown that if the ratio of $(CO)^2$ to CO_2 be less than about 0.4, the ratio $CO \times H_2O$ to $CO_2 \times H_2$ (water-gas reaction) may be as low as 0.06 to 0.07 before etching begins to appear."

Otis (6) has worked out some interesting examples to show the effects of changing only the amount of water vapor present, assuming a typical combusted-gas atmosphere produced from coke-oven gas and having the following analysis: 10 percent CO; 5 percent CO_2; 20 percent H_2; and 65 percent N_2.

The results of changing the water-vapor content only, as based on the water-gas reaction, are shown in Table IV. The column headed "Remarks" indicates the expected effect on steel heated in this atmosphere under the conditions indicated.

TABLE IV

EFFECTS OF WATER-GAS REACTION ON A TYPICAL FURNACE ATMOSPHERE (CONSISTING OF 5 PERCENT CO_2, 10 PERCENT CO AND 20 PERCENT H_2) CAUSED BY CHANGING ONLY THE MOISTURE CONTENT

Percent H_2O	Dew Point deg F	$\frac{(CO)\times(H_2O)}{(CO_2)\times(H_2)} = K$	Remarks
0.1	— 9	$\frac{0.1\times0.001}{0.05\times0.20}=0.01$	Will etch
0.5	+28	$\frac{0.1\times0.005}{0.01}=0.05$	Likely to etch
1.0	+46	$\frac{0.1\times0.01}{0.01}=0.10$	Will neither etch nor oxidize
2.0	+64	$\frac{0.1\times0.02}{0.01}=0.20$	Desirable operating range
4.0	+84	$\frac{0.1\times0.04}{0.01}=0.40$	Will not etch but may blue during slow-cool because of excess H_2O

The requirement by Marshall that the ratio $(CO)^2$ to CO_2 be less than 0.4 is met by this particular gas which actually gives $(0.10)^2$ to $0.05 = 0.2$.

The other requirement stated by him was that the water-gas-equilibrium constant value should be above 0.06 to prevent etching.

That the producer-gas reaction just mentioned plays a part in this reaction is borne out by the fact that etching is normally accompanied by a carbon deposit around the affected area.

DECARBURIZING AND CARBURIZING REACTIONS

Thus far in Part II, we have considered reactions which will either oxidize and scale the surface of a metal, or maintain it free of oxides, and/or reduce any oxides back to pure metal. Now we shall be concerned with the effects of the atmosphere gases upon the carbon content of iron (see Table III). For instance, if it is desired to "clean-harden" a carbon steel, the atmosphere must prevent oxidation and at the same time maintain the carbon content at the surface so that carbon is neither added nor removed. The difference in appearance between a scaled part hardened in an air atmosphere and one clean-hardened in a protective atmosphere is readily apparent in the two drill-chuck bodies shown in FIG. 11. The surface of the clean-hardened part is not roughened or pitted, and does not require subsequent cleaning operations. Also, the part is hard at the surface as well as in the body.

A consideration of the separate gases in Table III discloses some interesting facts. Oxygen is both oxidiz-

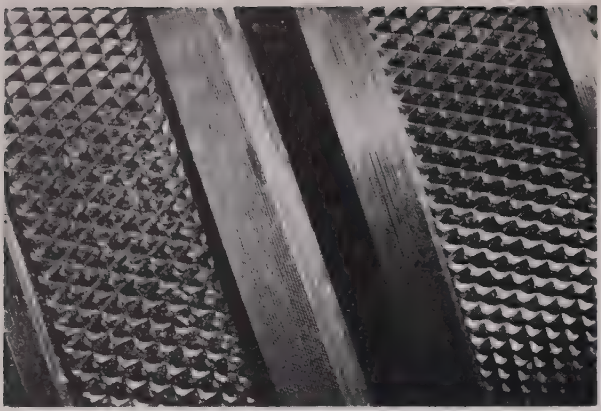


Fig. 11. Drill chuck bodies hardened in air (left) and in protective atmosphere (right), showing the difference in surface condition

ing and decarburizing to iron and iron carbide. If scaling is rapid, the iron is removed as fast as the carbon, and the finished surface (with scale removed) usually shows no decarburization. If the oxidizing process is slow, however, carbon may be removed faster than the iron, and decarburization results. The reactions of oxygen with carbon and with iron carbide are

$$O_2+C=CO_2 \tag{15}$$

$$O_2+Fe_3C=3Fe+CO_2 \tag{16}$$

Water vapor will oxidize and is also strongly decarburizing. The most important property of water vapor, however, seems to be its effect upon the equilibrium conditions of the other gases. For instance, a very small amount of water vapor added to pure dry hydrogen will cause the atmosphere to become very decarburizing. The same condition exists with dry nitrogen.

The general effect of adding water vapor to protective atmospheres is to retard reactions of hydrocarbon gases with iron, and to neutralize the carbon potential of certain reformed hydrocarbon gases. Consequently, a low dew point or low moisture content must be maintained in any atmosphere to prevent decarburization in a satisfactory manner. The effect of water vapor on the carbon potential of a furnace atmosphere is so definite and reliable that adjusting the dew point is now recognized as one of the best methods of controlling accurately the carbon potential of a furnace atmosphere. The process of carbon restoration, which involves the replacing of carbon in decarburized surfaces, has received much attention in the last few years.(7) In practically all reports made on this process, the control of the furnace atmosphere has been effected by accurate adjustment of the water-vapor content.

Like the other oxidizing gases, CO_2 is decarburizing; also CO_2 not only will combine directly with iron and iron carbide, but will combine with hydrogen to produce water vapor by means of the water-gas reaction previously discussed. Therefore, to maintain a low dew point, it becomes necessary that CO_2 be almost entirely removed.

The effect of removing CO_2 and reducing water-vapor content is well illustrated in FIG. 12. Photomicrograph *B* in FIG. 12 shows a very definite band of decarburization after 10 minutes' treatment in an atmosphere containing CO_2 and H_2O. Photomicrograph *C* shows no carbon change when CO_2 is removed and the water vapor is reduced.

The reaction of CO_2 with iron carbide is

$$CO_2+Fe_3C=3Fe+2CO \tag{17}$$

This equation, being reversible, shows that to maintain an equilibrium between the gases and the iron carbide, a certain fixed relation of the CO and CO_2 must exist. The curves in FIG. 13 indicate this relation to be a function of the temperature and carbon content. It is important to note that any single ratio of CO to CO_2 is neutral to only one carbon content at one particular temperature.

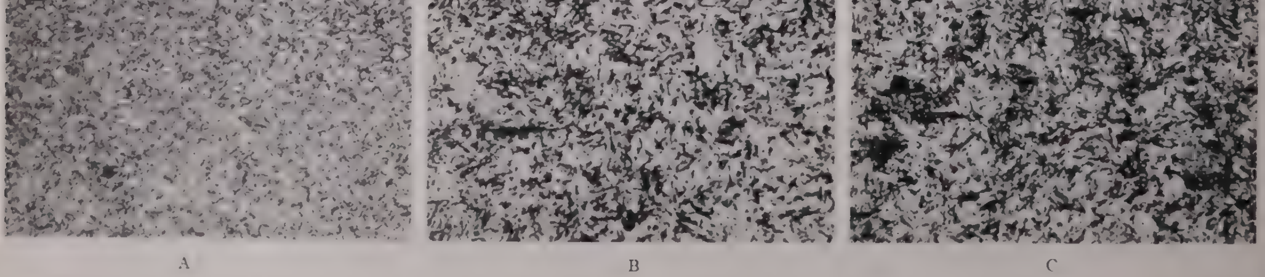


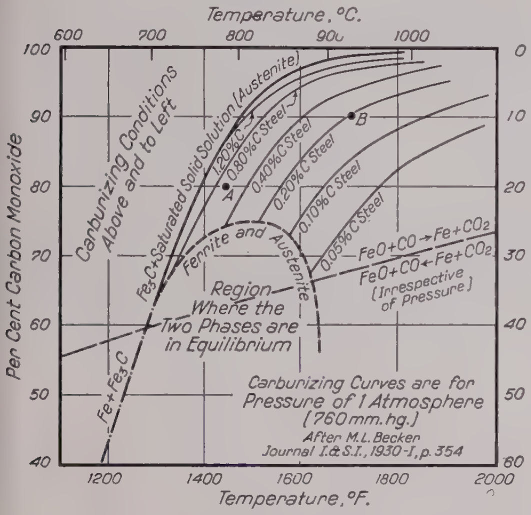
Fig. 12. Photomicrographs of 0.60 carbon steel showing the decarburizing effect of CO_2 and H_2O, and the elimination of this effect by removing the CO_2 and reducing the H_2O

A: Original sample of SAE 1060 steel (magnification in the photomicrographs, shown here as A. B, and C, is 250)

B: Sample treated 10 min at 1500 F in partially combusted gas containing 3.5% CO_2 and with a furnace dewpoint of +70 F. White band at surface indicates decarburization

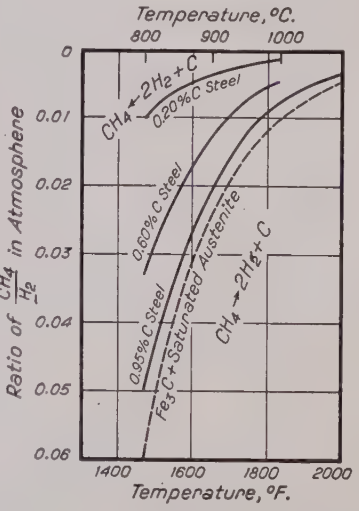
C: Sample treated 30 min at 1500 F in the same partially combusted gas with all CO_2 removed and the dew point in the furnace reduced to +24 F. Note absence of decarburization

For instance, a CO to CO_2 ratio which would be neutral to 0.4 percent carbon steel at 1650 F would, at the same time, be carburizing to 0.2 percent carbon steel and decarburizing to a steel containing 0.8 percent carbon. Also, if the same ratio of gases was maintained and the temperature increased, the 0.4 percent carbon steel would be in a carburizing range; and, if the temperature was decreased below 1650, it would be in a decarburizing range. To prevent decarburization, then, it is generally important to establish an equilibrium at the maximum temperature, since reaction rates increase with temperature.



← Fig. 13. Carburizing or decarburizing reactions of CO and CO_2, and their relation to carbon in the steel at different steel temperatures

Fig. 14. Carburizing or decarburizing equilibrium of methane (CH_4) with various carbon steels at different steel temperatures →



When it is desirable to carburize or add carbon to the surface of the steel being treated, it can readily be seen that gas conditions or equilibrium must be established which will cause the reactions to proceed toward the side of the equation on which iron carbide is produced. From Equation (17), it becomes evident that carbon monoxide is a carburizing gas.

The most active carburizing gases, however, are the hydrocarbons (8), such as methane (CH_4).

$$CH_4+3Fe=Fe_3C+2H_2 \qquad (18)$$

This equation shows that again the control of the reaction is based upon an equilibrium of two gases—the ratio of CH_4 to H_2. Fig. 14 clearly shows the effect of the reaction, which is dependent on the degree of carbon in the steel. Thus, for the carbon steel under the conditions in question, any gas which contains more hydrogen than the equilibrium mixture requires, will tend to decarburize. At the higher temperatures, a large amount of hydrogen is required to be in equilibrium with methane to cause decarburization. In other words, the presence of a relatively small amount of methane in a gas tends to make it carburizing, which is an important factor in furnace atmospheres for treating carbon steels.

FACTORS AFFECTING CHEMICAL REACTIONS

Although the theoretical equations of the various gas reactions have been considered at some length, various conditions which may be important factors have, up to this point, been disregarded. The following conditions may affect the practical application of the reactions.

Time

Most of the reactions discussed (except combustion) require an appreciable amount of time for completion to an extent sufficient to become important. For instance, the moisture content of an atmosphere for bright annealing of steel in a continuous furnace could be as high as 4 percent without blueing because of the short cooling time. This same atmosphere, if used in a bell-type batch furnace, would cause very bad discoloration and low temperature oxidation because of the very slow cooling cycle.

In the carburizing process, the depth of carbon penetration varies almost directly with time.

Etching, which would be completely absent in a continuous-cycle process that is completed in a matter of minutes, would become very serious in a batch process involving a cooling cycle of many hours' duration.

Temperature

Most of the chemical reactions just mentioned proceed rapidly at high temperatures. Clean iron oxidizes rather slowly at 800 F, even when heated in air, but scales in a few minutes at 1600 F. Carbon steels decarburize very slowly up to 1200 F, but do so with increasing rapidity at higher temperatures.

The significant temperature, however, is that of the surface of the metal being treated, rather than that of the furnace walls or the gas atmosphere. Ordinarily, however, the atmosphere at the surface of the metal is at practically the same temperature as the metal itself. To obtain uniform results over a metal surface, uniform temperature is obviously necessary.

Volume of Atmosphere Used

As mentioned before, reactions require a certain amount of time for completion. If the volume of a gas entering a given furnace is so great that fresh gas is continuously sweeping the work, gas-equilibrium conditions may never be reached.

Some reactions, such as that which produces etching, proceed best in a static atmosphere; whereas carburizing reactions, to proceed uniformly over all surfaces, require constant circulation.

Any atmosphere effect, if spread over a large surface of work being treated, may be negligible; whereas a large amount of atmosphere in proportion to the work surface presented may concentrate the effect.

Materials in Contact with Atmospheres

Many gas reactions proceed much more rapidly or completely when catalyzed by certain materials. As an example, the producer-gas reaction, Equation (14), is promoted by the presence of iron. The iron may be the work being treated, the alloy basket supporting the work, or even iron particles in the brick lining of the furnace chamber, assuming the atmosphere is in contact with the lining.

Impurities

Small amounts of impurities may contaminate the most carefully prepared atmospheres. Examples would be: moisture introduced into the furnace chamber by air or water entrapped in the work; moisture absorbed from the brickwork; or steam given off from water seals that are not kept cool.

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The carbon potential of a given atmosphere may be increased by oil on parts entering the furnace or by hydrocarbon materials in the work, such as lubricants used in compacts of pressed powdered metals prepared for sintering.

SUMMARY

In this review of theoretical considerations, an attempt has been made to list and illustrate the principal chemical reactions which can and do take place in the furnace between the various gases comprising an atmosphere, and between the atmosphere and the work. Reference has also been made to literature and curves showing equilibriums for various gas combinations under specific conditions. However, as mentioned in the preceding paragraphs, there are many factors which may affect the results in actual production equipments.

The theoretical data should, in general, be considered useful as a guide to what may happen, rather than as a definite answer to what the result may be. Results may also be interpreted more easily if theoretical facts are understood.(9)

In attempting to apply theoretical data or to get a correct picture of conditions as they actually exist, certain factors should be kept in mind. When a sample of atmosphere gas is to be analyzed, it should be taken from a point where representative conditions exist and not from some stagnant location within the furnace.

A proper analysis of an atmosphere must consider the value of all the active gases separately—an analyzer giving total combustibles, by grouping together CO, H_2, and CH_4, would be of little help.

Moisture content also is very important in many applications and must not be overlooked. Care should be exercised to assure that no water condenses out of the sample before it reaches the measuring instrument.

Although the theoretical considerations may seem to make the use of protective atmospheres rather complex, the actual applications of protective atmospheres will prove to be relatively simple as they are clarified later in this serial.

(To be continued)

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SIMPLIFIED CALCULATION OF BLACK-BODY RADIATION

A radiation slide rule has been compiled for direct computation of the spectral distribution and the amount of radiant energy associated with a desired temperature. Conversion scales for different energy and temperature units are also incorporated

By ALFRED H. CANADA
General Engineering and Consulting Laboratory
General Electric Company

A. H. Canada

THE impetus given infrared development by the war has emphasized its usefulness in science and engineering. The need by engineers for standardization of terminology and of circuit techniques and characteristics of radiation-detection devices, so that they may be applied to infrared developments, has not only accented the need for an understanding and utilization of the Planck radiation functions for energy emitted by heated objects, but has also increased the necessity for simplification of these calculations.

In the application of bolometric and other types of sensitive radiation-detecting devices both to infrared spectroscopy and to military equipment there is occasion both for the expression of radiated energies, though they may be small, in equivalent terminology, and for rapid means of conversion and calculation. For example, if the minimum detectable signal is expressed in watts per square meter for one detector and Btu per square foot per hour for another device, one should not need to go through too many mathematical gymnastics to find a comparative basis between the two equipments. Furthermore, in the application of various types of photoemissive and photoconductive detectors to radiation measuring problems, the threshold spectral limit of sensitivity is particularly important.

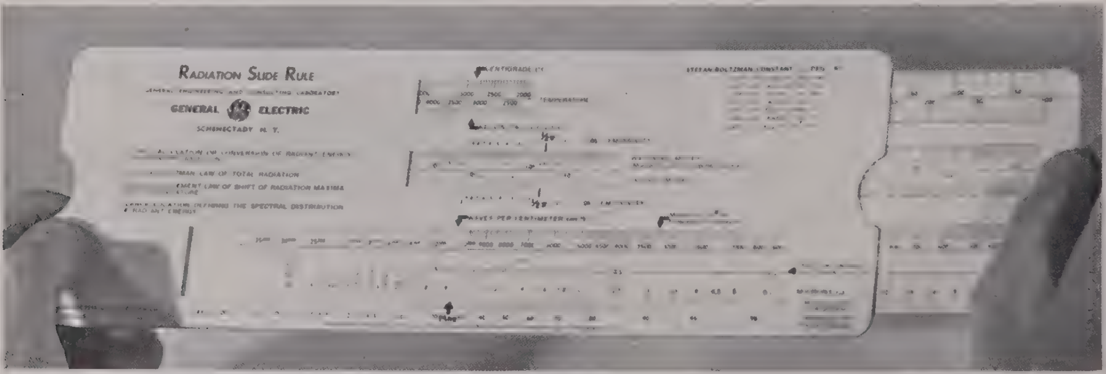

Fig. 1. The face of the radiation slide rule, containing energies and temperature in the metric system and the distribution-of-energy scale. The relative-luminosity curve appears at the left end of the micron scale

This is also true in the case of the window, or lens, materials to be utilized in radiation measurement. If, for instance, it is desirable to detect the energy radiated by an object at a particular temperature and if one wishes to evaluate the lead sulfide cell (sensitive to about 3.5 microns) for the particular application, it is important to know the distribution of the energy in the spectrum.

RADIATION LAWS

The radiation slide rule (FIG. 1) described in this article is a simple device for computing these various energy relationships. It is based on the well-known Planck equation defining the spectral distribution of radiant energy, the Wien displacement law of shift of the radiation maximum with temperature, and the Stefan-Boltzmann law of total radiation.

Planck's empirical equation

$$W_{\lambda}=C_1\lambda^{-5}\left(\epsilon^{\frac{C_2}{\lambda T}}-1\right)^{-1} \tag{1}$$

was derived to fit the distribution of energy in the spectrum from a black body at a particular temperature. Values and dimensions of the terms in this and later equations are given in the tabulation of nomenclature on the next page.

In lieu of a family of black-body radiation curves for various temperatures as classically illustrated, plotted with energy per unit area per unit wavelength as a function of wavelength, a ratio plot relative to λT is illustrated in FIG. 2. The data for this curve were obtained from *Miscellaneous Physical Tables—Planck's*

This article is so paged that without mutilating other articles, it can be readily removed for filing as a group of full-size consecutive pages.—EDITOR

Radiation Functions, sponsored by the National Bureau of Standards, where tables based on the λT relation are given. This curve is the spectral emittance ratio of energy per unit area per unit wavelength to energy per unit area per unit wavelength at the maximum point of the black-body distribution plotted against λT.

Referring again to Planck's equation, the ratio is equal to

$$\frac{W_\lambda}{W_{\lambda m}} = \frac{C_1\lambda^{-5}\left(\epsilon^{\frac{C_2}{\lambda T}}-1\right)^{-1}}{C_1\lambda_m^{-5}\left(\epsilon^{\frac{C_2}{\lambda m T}}-1\right)^{1}} \qquad (2)$$

By setting the derivative of Equation (1) equal to zero and solving, the relationship of the wavelength to the temperature at which W_λ is maximum is obtained. This is Wien's displacement law and is expressed

$$\lambda_m T = 2897 \qquad (3)$$

To compute the ratio in Equation (2) for a given argument of λT, consider the computation for λT at 0.375. In the following ratio the temperature cancels out, since one temperature of radiator is considered in Equation (2):

$$\frac{\lambda T}{\lambda_m T} = \frac{(0.375)}{2897} \quad \begin{matrix}\leftarrow \text{Given argument} \\ \leftarrow \text{Wien's law}\end{matrix} \qquad (4)$$

By substituting this ratio, the value of $\lambda_m T$ and the given argument in Equation (2), the energy ratio can be obtained. When computations are based on the λT relation and the ratio in Equation (2), the first radiation constant cancels out so that state of polarization or size of solid angle does not enter.

By integration of the Planck Equation (1) with respect to wavelength from zero to infinity the total radiated energy is obtained. This is then expressed in a lumped-constants relationship by the Stefan-Boltzmann law, which is

$$W = \rho\sigma T^4$$

or $\qquad (5)$

$$W = \rho\sigma(T^4 - T_0^4)$$

This equation yields the total energy radiated to cold space, or to temperature T_0, from a unit surface into

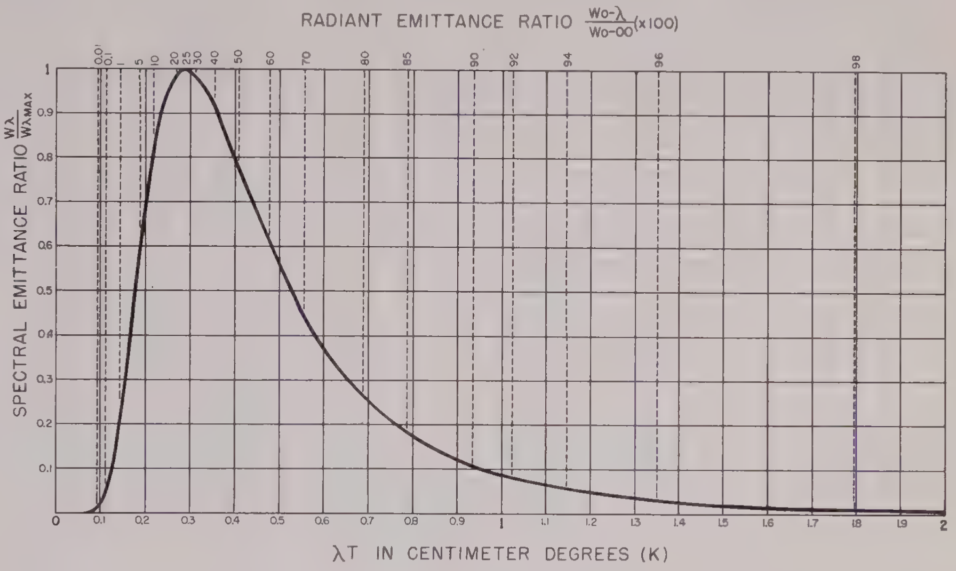

Fig. 2. Distribution of the energy radiated by a black body

NOMENCLATURE

Constants applicable to the radiation laws according to R. T. Birge (*Rev. of Mod. Phys.*, **3**, 233, 1941)

W_λ = Radiant energy emitted per unit area per unit range of wavelength

W = Radiant energy emitted per unit area

C_1 = First radiation constant

= $2\pi hc^2 = 3.740\times10^{-5}$ erg-cm² sec⁻¹ when W_λ denotes the emission of unpolarized radiation in unit range of wavelength per unit surface in 2π solid angle

= $2\pi hc = 4.990\times10^{-15}$ erg-cm when W_λ denotes energy density of unpolarized radiation

= $hc^2 = 5.950\times10^{-6}$ erg cm^{-2} sec^{-1} when W_λ denotes intensity of lineally polarized radiation in unit range of wavelength, per unit surface, per unit solid angle, perpendicularly to a surface

C_2 = 1.4385 cm-deg—second radiation constant

T = Absolute temperature of radiating body (°K)

T_0 = Absolute temperature of surroundings (°K)

λ = Wavelength in microns

λ_m = Wavelength in microns for maximum radiant energy

ϵ = 2.718—Napierian base

ρ = Emissivity factor (black body = 1)

σ = Stefan-Boltzmann constant

h = 6.624×10^{-27} erg-sec—Planck's constant of action

c = 2.99776×10^{10} cm sec^{-1}—velocity of light

2π solid angle. The energy is proportional to the emissivity factor (ρ), being the ratio of the energy from the given radiator to that from a black body at the same temperature. The various values of the Stefan-Boltzmann constant (σ), as used for a basis of the radiation slide rule, are given in Table I.

ABLE *I*

STEFAN-BOLTZMANN CONSTANTS BASED ON DEGREES KELVIN FOR THE VARIOUS ENERGY SCALES ON THE RADIATION SLIDE RULE.

5.672×10^{-5} erg cm^{-2} deg^{-4} sec^{-1}
5.672×10^{-8} watts meter^{-2} deg^{-4}
1.356×10^{-12} cal cm^{-2} deg^{-4} sec^{-1}
3.71×10^{-11} watts in $^{-2}$ deg^{-4}
1.825×10^{-8} Btu ft^{-2} deg^{-4} hr^{-1}
5.348×10^{-12} kw-hr ft^{-2} deg^{-4} hr^{-1}
4.602×10^{-9} kg-cal ft^{-2} deg^{-4} hr^{-1}

Restating these laws: Planck's equation defines the distribution of the energy in the spectrum or the shape of the black-body radiation curve; Wien's displacement law specifies the position of peak energy relative to wavelength; and the Stefan-Boltzmann law yields the total energy or area under the curve.

DESIGN OF RADIATION SLIDE RULE

To aid in the simplified handling of these radiation laws, the radiation slide rule has been compiled*. The principle of the device has been previously suggested and a few such slide rules constructed. As far as the author can determine, the idea was first proposed by M. Czerny, in Germany, and later rules were introduced in this country by G. Hass, of the Engineer Research and Development Laboratories at Fort Belvoir, Virginia. The slide rule described here has been materially expanded over those earlier rules to cover not only computation of total energy but the conversion of these values to other systems of units. Various temperature scales are included so that energy calculations can be based on scales other than Kelvin.

The Kelvin scale consists of two logarithmic cycles. A part of it is shown in FIG. 3. Aligned by the proper Stefan-Boltzmann constant are two total energy scales, watts per square meter and Btu per square foot per hour. These scales are also logarithmic. Since the total radiated energy is proportional to the fourth power of the absolute temperature, there are four log cycles for one log cycle of the Kelvin scale. These log cycles are positioned relative to the 1000 K point; thus, the total radiated energy for a body at 1000 K is 5.672×10^4 watts per square meter, or 1.825×10^4 Btu per square foot per hour. Other total energy scales, incorporated in the slide rule and available for ready conversion from one set of units to another, are those for which constants are given in Table I.

WAVELENGTH OF MAXIMA

Bearing a fixed relationship to temperature, as shown by Wien's displacement law, is the micron scale illustrated in FIG. 3. This, too, is a logarithmic cycle the same length as the logarithmic cycle of the Kelvin scale, but since wavelength maximum varies inversely with the absolute temperature, the logarithmic cycle is inverted.

For additional information, photon energies in electron volts are marked on the slide rule's micron scale to show their relationship to wavelength.

For use in spectroscopy, two of the scales make possible the conversion of microns to waves per centimeter. The waves-per-centimeter scale (reciprocal centimeters or wave numbers) consists of a logarithmic cycle inverted to the microns scale and of the same cycle length; thus, one micron is equivalent to 10,000 waves, 5 microns is equivalent to 2,000 waves, etc.

Since the interrelationship of the various total energy scales is fixed, the radiation slide rule can be used for the conversion of energy units. To simplify the changing of temperature values, Centigrade, Fahrenheit, and Rankine scales are included in their proper correlation to the Kelvin scale and are usable for temperature conversion.

EMISSIVITY LESS THAN ONE

The radiation slide rule may also be used for computing total radiated energy other than that from a black body. This is illustrated in FIG. 4. If a given temperature for a radiating black body is set on the index—for example 2100 K, as in FIG. 4—the total radiated energy is read opposite the index as 1.1×10^6 watts per square meter. If, however, the radiating body at 2100 K is not a black body but radiates only 30 percent as well as a black body, its emissivity then is 0.3 and the total energy radiated is 3.2×10^5 watts per square meter.

These values of radiant energy are considered to be those radiated by a unit surface into a 2π solid angle or a hemispherical solid angle. To obtain the energy radiated per steradian, or unit solid angle, one must divide by 2π. Since the scales are logarithmic, this can be accomplished by multiplying by the reciprocal of 2π, which is marked on the emissivity scale.

SPECTRAL DISTRIBUTION OF ENERGY

Thus far the radiation slide rule is only a means of conversion, and, with the exception of the emissivity, this conversion could be accomplished in tabular form or as a nomograph of the several scales. The main reason for the sliding part of the rule is noted in FIG. 5. The micron scale is on the slider. On the fixed part of the rule is a scale for percentage increment of energy falling below any wavelength, which is used to determine the distribution of the energy within the spectrum for a black-body radiator.

The use of this scale may be explained by the example in FIG. 5. The scale is set for 1000 K. The number 2.89

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*The rule, designated GEN-15, is printed on varnished card stock and is satisfactory for order-of-magnitude calculations. It may be obtained, postpaid, at \$.75 from the General Electric Company, 1 River Road, Schenectady, N. Y.

on the micron scale is opposite the index, indicating that the maximum of the black-body energy distribution curve occurs at this wavelength. Twenty-five percent also occurs at the index, which indicates that 25 percent of the total radiated energy of the black body at 1000 K will fall on the short-wavelength side of this maximum at 2.89 while 75 percent, or the remaining energy, will fall on the long-wavelength side. This scale can be used to determine the amount of radiant energy falling between any two wavelengths. For example, the energy falling between 5.5 microns and 9.5 microns is 20 percent (90 minus 70) of the total radiated energy from this black body at 1000 K. At this setting, the slide rule shows that less than one ten-thousandth of one percent of the energy of the black body falls within the visible spectrum.

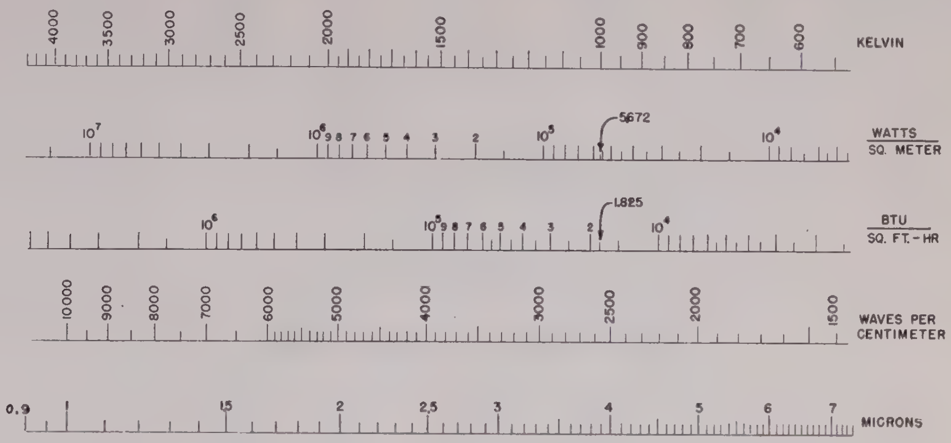

Fig. 3. Basic scales used on the radiation slide rule

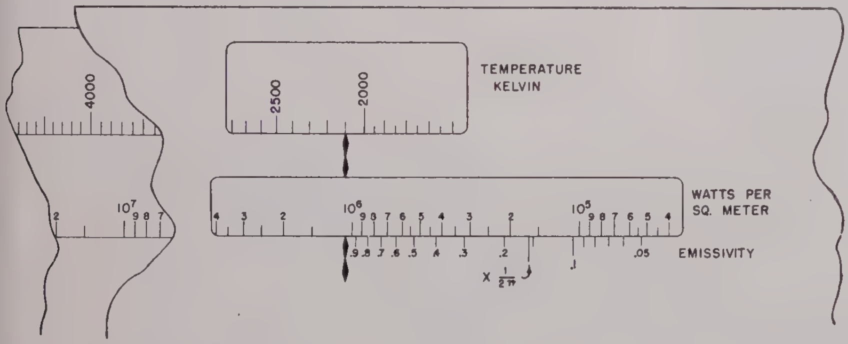

Fig. 4. A portion of the radiation slide rule illustrating the use of the emissivity scale and unit solid-angle mark

The distribution of the energy scale is applicable to any temperature setting of the slide rule. As higher temperatures are utilized, of course, a larger percentage increment falls within the visible portion of the spectrum.

The validity of this percentage-distribution scale depends upon the logarithmic construction of the slide rule. Illustrated in Fig. 2 is the radiant-emittance ratio of the energy between wavelength zero and λ to energy between zero and infinity. This is obtained by integration of Planck's equation within specific limits with respect to wavelength. The ratio may be shown to bear a fixed relationship to λT and is so plotted in Fig. 2. Since the micron scale is logarithmic, the spacings of the increment scale, corresponding with the spacings shown in Fig. 2, remain fixed for all settings of the temperature scale.

To increase the usefulness of the slide rule in the visible portion of the spectrum, a relative-luminosity curve for the eye is included on the visible-light portion of the micron scale (shown in Fig. 1). A separate nomogram printed on the rule shows specific characteristics of tungsten, giving color temperature and brightness in candles per square centimeter, as functions of the true temperature.

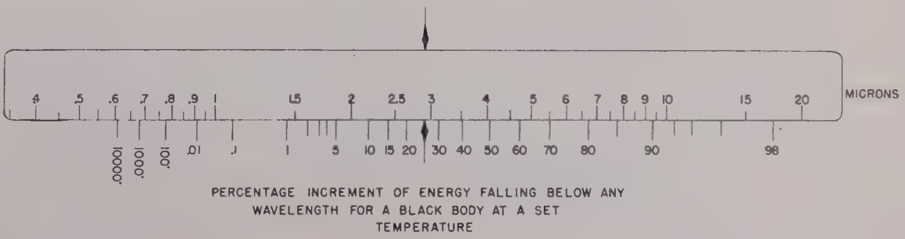

Fig. 5. Illustration of the slide-rule method for computing black-body energy distribution

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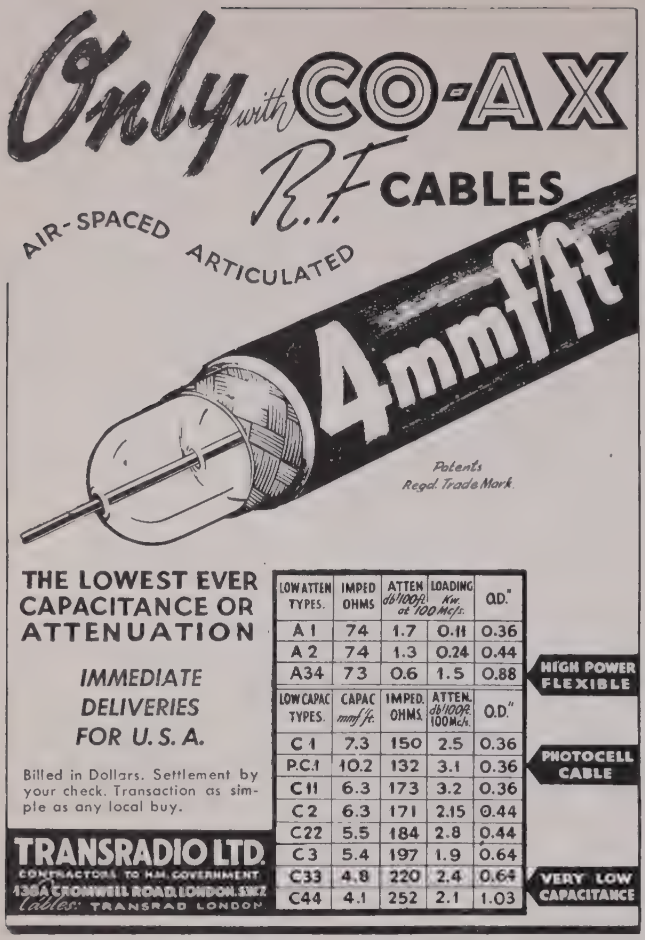

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A 2	74	1.3	0.24	0.44
A34	73	0.6	1.5	0.88

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LOW CAPAC TYPES.	CAPAC mmf/ft.	IMPED. OHMS	ATTEN. db/100ft. 100Mc/s.	O.D."
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P.C.1	10.2	132	3.1	0.36
C 11	6.3	173	3.2	0.36
C 2	6.3	171	2.15	0.44
C22	5.5	184	2.8	0.44
C 3	5.4	197	1.9	0.64
C33	4.8	220	2.4	0.64
C44	4.1	252	2.1	1.03

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SIMPLIFIED CALCULATION

(Continued from preceding page)

SAMPLE CALCULATIONS

Two problems may serve to illustrate the use of this radiation slide rule. The graphite plate of a particular metal-shell vacuum tube operates at 500 C. Carbon at 500 C has an emissivity of only about 0.08, or is only eight percent as good an energy radiator as a black body. If 500 C is set on the index, it is found that a black body radiates 2×10^4 watts per square meter while carbon, at its low value of emissivity, radiates 1.6×10^3 watts per square meter as read opposite the appropriate emissivity. This radiant energy is absorbed in the metal envelope of the tube. Assuming a temperature of 100 C at the metal, we may compute the energy radiated to the carbon by the metal. In this case, since the metal is the surrounding, the emissivity factor of the metal does not enter into the calculation. With 100 C set at the index the energy reading at the index is 1.1×10^3 watts per meter. By subtraction it is found that 500 watts per square meter is the net radiation retained at the metal envelope from plate dissipation.

If a glass envelope is used, the problem becomes much more complex, since some of the radiation is transmitted by the glass. It is then desirable to find how much of the radiated energy is transmitted. At 2.5 microns, the glass begins to be a poor transmitter of infrared radiation. On the percentage-increment scale, 2.5 microns for this particular temperature (100 C) falls at 6 percent. Thus approximately 6 percent of the energy is transmitted by the glass, while 94 percent of the energy radiated by the plate is absorbed by the glass. Since the percentage-increment scale is for black-body distribution, the percentage of energy transmitted is only an approximation.

In another device it is desirable to use a lead-sulfide photoconductive detector to measure the radiant energy from a black-body radiator varying between 1000 and 2000 F. To determine the order of accuracy to be expected in such an application, the spectral characteristics of the lead-sulfide cell are important. If it is assumed that the cell does not respond to wavelengths longer than 3.3 microns, then for 1000 F the percentage-increment scale will show that only about 20 percent of the energy from the source is available to the lead-sulfide cell to be converted into a usable signal. At 1500 F, reading the percentage-increment scale again, 40 per cent of the energy is available for signal at the lead-sulfide cell. At 2000 F, 3.3 microns falls opposite about 57 percent; thus, 57 percent of the energy of the black body at this temperature is available for signal at the lead-sulfide cell.

The complete radiation slide rule has been constructed and made available for distribution in the hope that it will aid in the understanding of the radiation laws and materially simplify calculations connected with problems in illumination, applications of infrared, radiant heating, temperature measurement by radiometry, infrared spectroscopy, spectroradiometry, and heat transfer.

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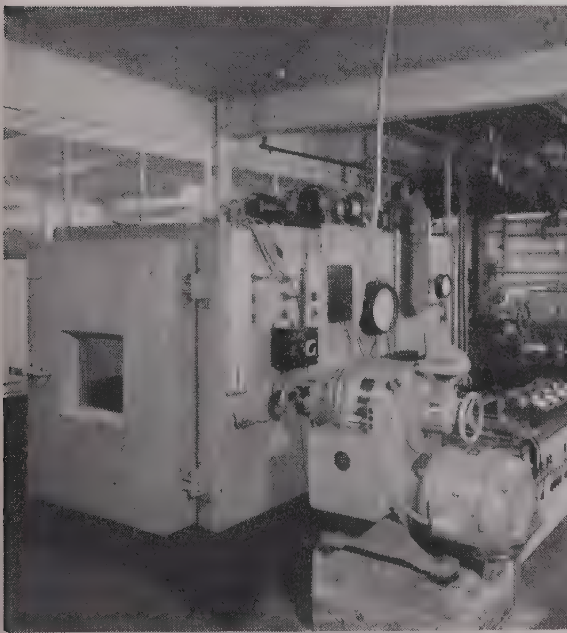
Variation of operating conditions — from high speeds to high altitudes — calls for diverse carbon brush characteristics. Special testing equipment such as the High Altitude Test Chamber — which simulates temperatures and air pressures at 35,000 ft.—enables Speer engineers to observe brushes at work under actual conditions . . . provide characteristics that serve best. A reason you can be sure that every Speer brush you use is fit for the job.



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HIGH LIGHTS AND SIDE LIGHTS

Electronic Eye Operates Street Lights

Housing for the electronic eye which can see dusk or dawn approaching and turn on individual street lights is slipped into place on a demonstration light. The center transparent tube turns the light on automatically when the early shadows of dusk or the first rays of dawn appear

An electronic eye has been developed which is able to "see" dusk and dawn approaching and turn on or off individual street lights.

This photoelectric control device will be installed on single street lights, whereas most automatic time-control devices now in use turn on, or off, a series of street lights at a predetermined time.

The new control turns on street lights when the greatest danger of accident lurks in hazy twilight shadows.

A gas-filled phototube, an electronic device sensitive to red light, is used as the "brain" of this automatic lamplighter; such a phototube was selected because the light of the setting sun in early evening is nearer the red end of the color spectrum.

The small cylindrical tube contains a coated, negatively charged, metal plate or cathode, which, when struck by the red beams of light or reduced light intensity, produces electrons which jump to the positively charged anode, generating a small electric current.

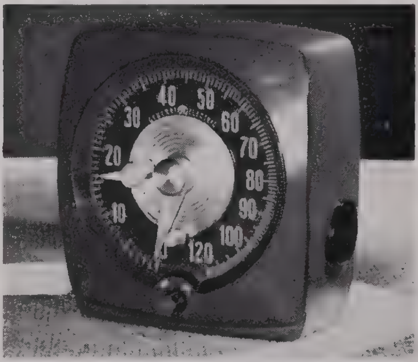
This current is carried through two amplifier tubes, which boost the power sufficiently to turn on the street light. The increase of light intensity in early morning will cause the phototube to reverse its turning-on operation.

The phototube will operate when outdoor light intensity reaches a level of from one to six foot-candles, the light intensity noticeable at twilight when objects some 500 feet distant become hazy to the observer.

The individual photoelectric control unit can be plugged into a single street light equipped with a plug receptacle. A little window, shielded from the direct rays of the setting or rising sun, will face the north and receive the light impulses.

New Interval Timer

A new automatic interval timer is now available in four models to fit a wide variety of applications for hobby, home, and laboratory. Powered by a synchronous, self-starting, permanently lubricated Telechron motor, the new timer operates on a 120-volt, 60-cycle a-c circuit with a maximum load of 1200 watts. Enclosed in an acid-resistant, gray plastic case, it weighs just two pounds. The dial is protected by a shatterproof plastic window.



One of four available new automatic interval timers, suitable for timing and controlling numerous devices, from electric household appliances to diathermy equipment

A triple-action control knob permits manual or automatic operation. A control pointer for setting the desired time period and a timing pointer which measures off the cycle are made of anodized aluminum. At the end of any cycle, the timer resets automatically. Equipment to be controlled can easily be plugged into the inlet receptacle on the side of the case.

Timers to measure the following time intervals are available:

0 to 120 seconds: Suitable for use in a wide range of photographic and other processes which require a short time cycle.

0 to 15 minutes: For controlling sunlamps, heat lamps, heat pads, and electric mixers in the home, and diathermy equipment and centrifuges in hospitals and doctors' offices.

0 to 2 hours: Can be used by pottery makers, chemists, and hobbyists for timing ovens and heating devices and by housewives for controlling electric casseroles and roasters.

0 to 12 hours: For timing long roasting and baking processes, battery-charging equipment, and other apparatus requiring a long time cycle.

Steering Recorder

A ship's course can now be automatically and continuously recorded. The "ship steering recorder" marks the ship's rudder position and compass direction and calculates on a moving roll of paper deviations as slight as two-tenths of a degree from the set course. Nine of the instruments have been delivered to the U.S. Navy for experimental installation in several destroyer and submarine chart rooms.

The steering recorder takes up no more room than a table-model radio-phonograph. The record is made on a 12-inch-wide roll of waxed paper which passes beneath metal points connected electrically with the ship's rudder and compass. At low speed, the instrument can make a continuous eight-day record without attention.

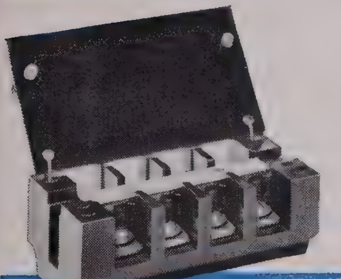
No permanent installations of the recorder have been made aboard ship as yet. The Navy is using the instruments at the present time to check the accuracy of experimental "automatic pilots" for ships.

Pictures with a Comb

The electricity that makes a girl's hair crackle when she combs it finally has been put to use. Advised by laboratory engineers that the crackle is worth some 8000 to 10,000 volts of potential electricity, a photographer succeeded in making it ionize a high-speed phototube, enabling a girl combing her hair to take a picture of herself. The novel method of photography was accomplished by attaching a metallic collector rod to an ordinary hand comb and then connecting the rod to the trigger electrodes of high-speed photoflash lamps. Each stroke of the comb supplied the 8000 volts necessary to set off the photolamps

Digest

TIMELY HIGHLIGHTS ON G-E COMPONENTS

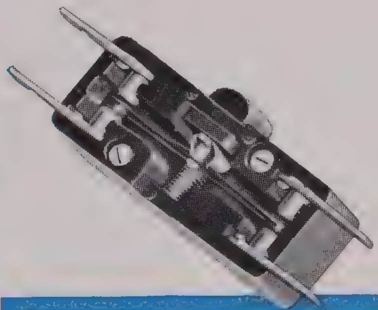


SIMPLIFY CONTROL WIRING WITH THESE TERMINAL BOARDS

Easy-action hinged covers protect control wiring, help give your product a neat appearance. Hook-ups are easy with the hard-gripping connectors. Simply strip the wire end, screw down the connector on the bare wire. Blocks are durable, too, constructed of strong Textolite with reinforced barriers between poles to insure against breakage. Marking strips are reversible—white on one side, black on the other. These terminal boards are available with 4 to 12 poles, 2 inches wide, 1¼ inches high. Send for bulletin GEA-1497C.

HOLDS OUTPUT VOLTAGE CONSTANT

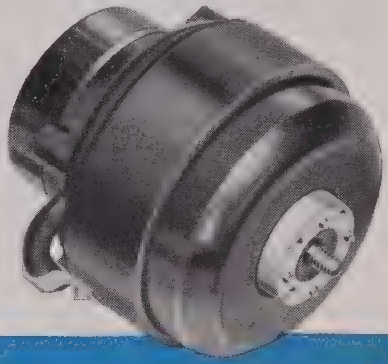
This latest addition to G.E.'s line of automatic voltage stabilizers comes in 15-, 25-, and 50-va ratings. Output is 115 volts, 60 cycles. The small size of the unit makes it particularly applicable to shallow-depth installations in many types of equipment. You may have a job for this unit which will give you automatically stabilized output voltage at a low cost. There are no moving parts, no adjustments to make; long service is assured. Check bulletin GEA-3634B for more information about this and other G-E voltage stabilizers.



LOOKING FOR LIGHTWEIGHT SWITCHES?

Switchettes* are designed for applications which require a manually operated electric switch in a limited space. Though small, these switchettes are lightning fast in action and are built to withstand severe service. A wide variety of forms and terminal arrangements makes them particularly useful where special circuit arrangements are necessary. Switchette shown above has one normally open and one normally closed circuit, transferable when button is depressed. Check bulletin GEA-4888.

*Switchette is General Electric's trade name for these small snap switches.



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☐ **GEA-4888** Switchettes
☐ **GEC-219** Unit-bearing Fan Motor

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NEW PRODUCTS: AND WHAT THEIR MAKERS HAVE TO SAY ABOUT THEM

Fluorescent Light Shade

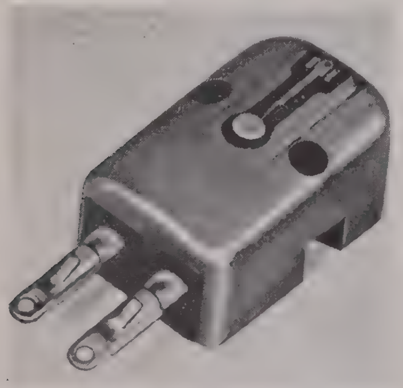
A new plastic diffusion shade diffuses the natural blue-white glare of fluorescent lighting without reducing light value. Finished in fluted crystal-clean plastic, with highly polished metal strips, the shade is easily cleaned, and is adaptable to overhead, vertical, or horizontal fixtures. The shade clamps lightly but firmly on the light tube, and requires no nails, screws, rivets, or other extra fixtures. Standard models come in lengths ranging from 16 to 40 in. Commercial models are also available in almost any length or color to meet channel lighting requirements.—*Lee-Bert Inc., 900 Lapeer St., Saginaw, Michigan.*

Pipe Bender

A new lightweight portable Champ tool forms smooth uniform pipe-bending operations right on the job. Weight has been kept down to a minimum without loss of strength; the combined weight of the jack and frame is only 83 lb. A removable hydraulic jack simplifies the service problem, as well as being useful for many other purposes. Open-jaw construction speeds up production. The 30-in. steel frame is electrically welded and heavily reinforced. The tool is furnished complete with several sizes of dies.—*Electric Cord Co., 30 Church St., New York 7, N. Y.*

Cartridge

A new variable-reluctance cartridge designed especially for the new long-playing records. The cartridge, which features a low-mass stylus assembly and high compliance for more faithful tracking, is one-third smaller than previous models. The improved shape makes it more universally adaptable to various tone arms and also affords greater clearance for record changers. The stylus is a sapphire measuring one mil in diameter, as required by the new microgroove recordings.—*General Electric Co., Electronics Department, Electronics Park, Syracuse, N. Y.*



Oscilloscopes

The No. 90902, No. 90903, and No. 90905 rack panel oscilloscopes for two-, three- and five-inch tubes respectively, are inexpensive basic units comprising power supply, brilliancy and centering controls, safety features, magnetic shielding, switches, etc. As a transmitter monitor, no additional equipment or accessories are required. However, by the addition of such units as sweeps, pulse generators, amplifiers, servo sweeps, etc., all of which can be conveniently and neatly constructed on companion rack panels, the original unit can be expanded to serve many industrial and laboratory applications.—*James Millen Manufacturing Co., Inc., Malden, Mass.*

Smoke-density Recorder

A new electronically operated smoke-density recorder accurately measures and records the density of smoke or dust in flues or ducts. The instrument consists of a standard electronic recorder, a bolometer-type smoke detector, and a sealed-beam light source.

The smoke detector and the light source are used as the primary element. They are installed on opposite sides of the smoke passage so that the beam from the light source is directed at the tungsten filament of the bolometer. The amount of radiation reaching the filament is dependent on the density of the smoke or dust; the temperature of the filament is dependent on the amount of radiation reaching it. The filament temperature is measured by the electronic recorder in terms of smoke density.—*Bailey Meter Co., 1050 Ivanhoe Road, Cleveland 10, Ohio.*

Pressure Lubricant

A new dry lubricant named Molykote consists essentially of molybdenum disulfide powder and has the appearance of graphite, although it contains none. With light rubbing, it adheres tenaciously to even the smoothest surfaces. It has a low friction coefficient, and the capacity to prevent galling, seizing, or metal-to-metal contact at bearing pressures well over 100,000 psi, and at either high or low sliding velocities. Ten ounces will cover 500 sq ft of smooth metal surface with a shiny coating. It is equally suitable for high, low, and room temperatures. When used on screw fasteners or press fits, assembly takes place at a smoothly increasing torque, or force, without jerking. —*The Alpha Corp., Greenwich, Conn.*

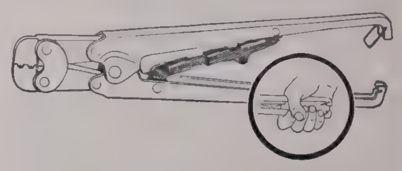
Snap Nut

A new spring-steel snap nut makes quick work of anchoring nut-to-panel for blind attachments. No welding, riveting, clinching, or special tools are necessary—the nut is simply pressed into assembly position. It is attached directly from the work surface instead of reverse side of panel. It snaps into a $\frac{9}{32}$ in. square hole in panels 0.037 in. to 0.055 in. thick, and is designed for easy entrance of screw, even in cases of extreme misalignment of panels.

As the screw is driven, the arched spring arms of the nut expand just enough to permit entry of the screw, locking the fastener to the inner panel, and at the same time binding against the root of the screw thread. The fastener will accommodate both No. 8 and No. 10 sheet-metal screws, the larger size merely expanding the spring arms further apart. It will withstand a tightening torque of 35 to 45 in-lb.—*Prestole Corporation, 3121 Bellevue Road, Toledo 6, Ohio.*

Crimping Tool

A new line of hand tools, named Certi-Crimp, for wiring applications requiring installation of solderless terminals by manually operated tools, eliminate the possibility of faulty electrical connections resulting from operator fatigue or carelessness. These tools utilize a simple yet effective device that prevents re-opening of the tool for admission of a new terminal until it has been completely closed for a perfect crimp on a previous terminal. Operation of the tool is unaffected by the Certi-Crimp feature, which is so constructed that it cannot be tampered with nor changed without obvious damage—*Aircraft-Marine Products, Inc., 1540 N. 4th St., Harrisburg, Pa.*



Starting Switches

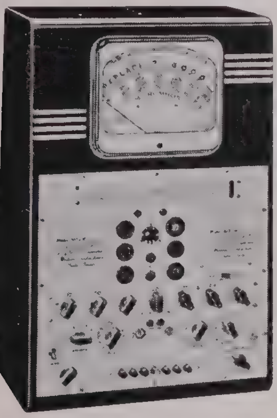
A new line of manual starting switches for use with fractional-horsepower motors. The switches are furnished in five different types: with general-purpose enclosure; without enclosure; a combination unit and selector switch; with cast-iron enclosure for wet locations; and a similar type for dusty or hazardous locations. An important feature of each type is a molded base of moisture-resisting insulating material which mounts and encloses the mechanism and contacts. This particular construction serves not only to protect the operating parts from dust and physical contact, but to direct the heat concentration to the sturdy bimetallic tripping device, thus assuring quick and positive action of the overload.—*General Electric Co., Control Division, Apparatus Dept., Schenectady 5, N. Y.*

Magnetic Starters

The new Bulletin 4111 Size 1 a-c magnetic starters are for nonreversing across-the-line starting of polyphase squirrel-cage induction motors and single-phase motors. These starters are available with open-type construction or with NEMA Type 1 general-purpose enclosures. They are suitable for use with separate pilot devices for two- or three-wire remote control, or can be supplied with local control pushbutton stations, or selector switches. Distinctive features include compact unit construction; high arc-interruption capacity; reliable thermal overload protection; and complete accessibility of parts.—*Ward Leonard Electric Co., Mount Vernon, N. Y.*

Tube Tester

The Model 533 DM display tube tester for the radio serviceman has been designed as a tube merchandiser which permits customers to see the condition of their own tubes. A nine-inch illuminated scale reads: Replace, Doubtful, and Good; thus customers can easily interpret actual test of their tubes.



The instrument is precision-built and incorporates the dynamic mutual conductance circuits. Flexibility has been provided in selector switches to take care of unusual base-pin connections. It tests all present-day tubes, and provision has been made for new tube designs so that tester will not soon become obsolete. The meter shows micromho ranges of 0 to 3000, 0 to 6000, and 0 to 15,000. Roll chart in panel makes tube data easily and quickly available.—*The Hickok Electrical Instrument Co., 10577 Dupont Ave., Cleveland 8, Ohio.*

Control Mechanism

A new pneumatic control mechanism for use in flow-controlling instruments. The housing for the new unit consists of a one-piece die casting; thus all component parts can be maintained in a fixed relationship to each other. Working parts are made from precision castings or heavy stampings, precision trimmed and carefully inspected to assure interchangeability. The assembly can be removed from the control instrument for cleaning or repairing, without disturbing the process, by simply flicking the transfer valve to the "service" position, disconnecting a single air line, and removing four screws. A minimum of tubing connections eliminates air-leakage troubles. Alignment of pen and index is assured throughout the range because both index and input links swing on a common center.—*Fischer & Porter Co., Dept. 7F-N, Hatboro, Pa.*

TRADE LITERATURE

MAGNET CHARGER—The important features of Model 107 are briefly presented by descriptive text and illustrations. Some typical newly developed adapters for production charging of industrial magnets are also illustrated. Six pages.—*Radio Frequency Laboratories, Inc., Boonton, New Jersey.*

TRANSFORMERS—A well-arranged bulletin outlining the construction and application of distribution transformers. Tabulations of ratings and application data together with illustrations and dimensional diagrams supplement the text. Bulletin No. 210-01. Eight pages.—*American Transformer Co., 178 Emmet St., Newark 5, N. J.*

ARC WELDER—Describes seven features for performance—generator, coupling, base, engine, auxiliary power outlet, calibrated dual control, and trailer—of a portable engine-driven single-operator arc welder. Bulletin GEA-4886. Four pages.—*General Electric Co., Apparatus Dept., Schenectady 5, N. Y.*

CORROSION—A handsome, neatly assembled booklet titled "Salt as a Corrosion Problem" touching on a bit of ancient history in the introduction. The corrosion problems encountered and solved by the salt industry is the subject of the first half, the remainder of the contents being devoted to the use of brine solutions and equipment for handling them in chemical and process industries. Twenty-four pages.—*International Nickel Co., Inc., 67 Wall St., New York 5, N. Y.*

DEHYDRATOR—The Type 1900 motor-driven self-activating automatic dehydrator is described and illustrated together with accessories for the unit. Bulletin 85. Four pages.—*Andrew Corp., 363 East 75th St., Chicago 19, Ill.*

INSTRUMENTS—Four well-prepared bulletins are offered under this general subject, the specific subject of each bulletin being thoroughly treated with respect to products, fundamentals, and applications. In each instance photographic illustrations, dimensional diagrams, schematic sketches, charts, and tables supplement the text. The catalogs are: "pH and Conductivity," Catalog 15-12, Forty-four pages; "Electronic Potentiometers," Catalog 15-13, Thirty-two pages; "Pressure and Vacuum Gauges," Catalog No. 7000, Thirty-two pages; and "Instruments for Treatment of Sewage and Industrial Wastes," Bulletin No. 7301, Forty-four pages.—*Brown Instrument Co., Div. of Minneapolis-Honeywell Regulator Co., Philadelphia 44, Pa.*

DRILL PRESS—Both bench and floor models of the 14-in. precision drill presses are shown, as well as motors, controls, extra spindles, and other drill-press accessories. Diagrams show important dimensions, and specifications and prices are listed. Catalog No. 400. Eight pages. *South Bend Lathe Works, 425 E. Madison St., South Bend 22, Indiana.*

FLUORESCENT FIXTURES—Controlled lighting by use of Hollophane Controlens is the subject of this brochure. Installation data is given for surface-mounted and recessed (both flat and curved) fluorescent fixtures, alone and in combination with incandescent accent lights. Bulletin No. 31-F. Eight pages. *Sunbeam Lighting Co., 777 East 14th St., Los Angeles 21, Calif.*

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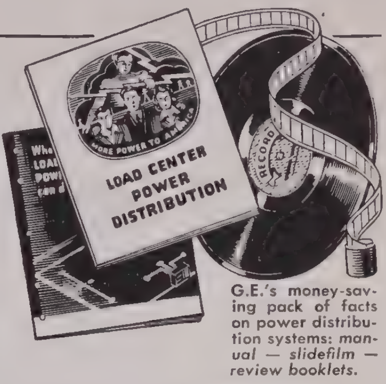

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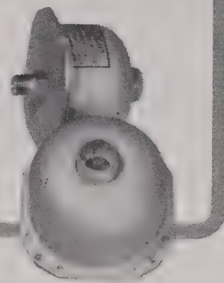

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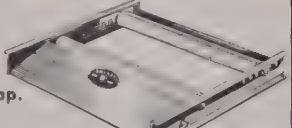

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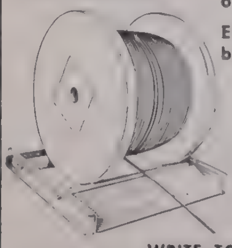

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BOOK REVIEWS

(Available books may be purchased through the GENERAL ELECTRIC REVIEW for domestic delivery; none sent on approval.)

THE MANUFACTURE OF GLASS

L. M. Angus-Butterworth—Pitman Publishing Corp., New York, Chicago. 1948. 286 pp. $6.00.

The author writes his book from an English background, with very definite interests in the historical development, in the manufacturing processes of glassmaking, and in the economic situations created by new glassmaking techniques.

The book comprises six sections labelled I: History, II: Composition and Properties, III: Plant, IV: Manufacture, V: Products and Uses, VI: Sundries. The sections on Plant and Manufacture occupy half of the book and sometimes go into extreme details in the descriptions of certain devices such as a push-bar stacker of glass containers and the various models of automatic presses for tumblers. The historical development of a number of industries is given in some detail, and includes lehrs, handworking methods, pressed glass, window glass, plate glass, sheet glass, and glass containers.

Section II, on Composition and Properties, is not particularly strong. The only compositions in the book refer to some colored glasses. The Table of Materials, Formulae and Molecular Weights needs thorough review and modernizing. "Arsenic" is not As_40_6 and Boric Acid is not H_2BO_3. The chapter contains other glaring errors of a similar kind. The division of the raw materials from which glasses are made into classes called acidic oxides, basic oxides, and flues is not technically good.

A section on stained glass is due mainly to the author's father.

An Appendix contains the details of the organizations of the glass industry in England and covers the glass guilds, research institutions, the Technical Society, institutions, and trade associations. A select Bibliography of Works in English relating to glass—its history, manufacture, and uses—contains old and new references. The Journal of the American Ceramic Society, however, is not listed.

LOUIS NAVIAS

PRINCIPLES AND METHODS OF TELEMETERING

Perry A. Borden and Gustave M. Thynell—Reinhold Publishing Corp., New York. 1948. 230 pp. $4.50.

Instrument engineers and others concerned with electrical, pneumatic, hydraulic, and other measurements made available at a distance from the point of measurement will find much of interest in this book, the first of its kind in English. Although this volume, the work of two Bristol Company engineers, has appeared in the same year as an AIEE revised report on the same subject, readers will find little or no duplication between the two publications. The authors have resisted the temptation merely to reproduce, with minor revisions, a well illustrated and very comprehensive descriptive article by one of them appearing in serial form in *Instruments* a few years ago. They have instead given the industry a thoroughly readable book in which illustrated descriptions of specific types of telemeters are introduced at the proper point in a logical exposition of the basic principles involved.

Valuable chapters include brief treatment of interconnecting metallic channels and of carrier channels, although obviously in a volume of this modest size it is not possible to cover either of those subjects completely.

A classified bibliography and a list of relevant patents materially enhance the value of this unique textbook, which by no means limits itself to the types of instruments built by the company with which the authors are associated.

GEORGE S. LUNGE

SOME ASPECTS OF THE LUMINESCENCE OF SOLIDS

F. A. Kröger—Elsevier Publishing Co., Inc., New York. 1948. 322 pp. $5.50.

This is a refreshing book. It is packed with first-hand information, concisely presented, and offers instruction to the student and suggestions to the expert. Facts are accompanied by well-knit and readable arguments in support of the explanations offered. Its literary style is clear and expressive. Here are no hackneyed statements but rather the lively phrasing of one who has knowledge and enthusiasm and has set himself gladly to the task of exposition.

The material is admittedly confined to the experimental work in which the author has been an active participator as a member of the Philips Lamp Company in Holland. It covers, however, most of the topics in luminescence that are of present interest—some very sketchily, others very fully. The book is the expression of the author's personality. The reader will not always agree with it, but he will always be interested.

The first chapter is the broadest in treatment. With its 53 pages of text, 39 pages of tables, and eight significant figures, it offers a short and illuminating survey. Its discussion of the energy relationships in luminescent crystals necessarily requires careful reading, but it is well within the comprehension of anyone with scientific training. This is followed by a presentation of the various phenomena of luminescence. An important feature is a lexicon of phosphors, referenced according to activator elements.

It is in the later chapters that the author discusses his specific interests. He describes at length his careful experiments undertaken to prove that the valence of manganese as an activator may, in many phosphors, be four as well as two, as basis for a shift in luminescence from green to red. He describes the effectiveness of titanium as an activator, thereby encouraging wider consideration of the importance of this element. He describes the luminescence of tungstates and molybdates, alone and combined, and the role of activators, more particularly lead, samarium, and uranium. Special stress is laid upon the relationship between absorption and excitation.

A final chapter treats of the variations in character of luminescence with temperature, a topic of importance to both engineer and theorist. The two theoretical approaches to an understanding are presented ably and sympathetically.

The book is well documented, with 74 figures and 27 tables; it is well bound and pleasing typographically except for occasional slips. Headings to the tables would be an improvement. It can be heartily commended to all serious students of the subject, both for the pleasure of reading and for the satisfaction of an increased understanding.

GORTON R. FONDA

LIBRARY NOTES

ON ARTICLES IN OTHER TECHNICAL JOURNALS

AIR CONDITIONING

Frequency of Starting of Room Coolers, by J. W. Anderson.
Elec. Wld., July 17, 1948; v. 129, pp. 72-74, 133.

An analysis of room coolers as they affect distribution circuits and loads.

BEARINGS

Bearing Metals, by H. R. Clauser.
Mat. & Methods, Aug. 1948; v. 28, pp. 75-86.

Outlines the requirements of sleeve-bearing materials, and describes properties and characteristics of the many different bearing metals.

CAMS

Analyzing Circular-arc Cams, by Philip K. Slaymaker.
Mach. Design, July 1948; v. 20, pp. 129-131.

Simple construction based on the familiar Scotch yoke permits rapid determination of velocity and acceleration.

COOLING TOWERS

Maintenance of Cooling Towers, by James G. DeFlon.
Heat. & Vent., July 1948; v. 45, pp. 57-61.

Tells what danger signals to look for and what steps can be taken to prolong the life and increase the efficiency of various types.

DAYLIGHT

Duration and Intensity of Sunshine: Part IV—Effect of Atmosphere, by Frank Benford.
Illum. Engng., July 1948; v. 43, pp. 699-710.

The fourth installment of a study on the nature of sunshine.

DIES

Better Steel Devised for Hubbing, by A. L. Pranses.
Am. Mach., July 29, 1948; v. 92, pp. 84-87.

The term "hubbing" denotes the process for manufacturing die cavities wherein a master die of hardened tool steel is forced into a block of soft steel to produce a cavity of the desired size and shape.

ELECTRETS

The Electret, by F. Gutmann.
Rev. of Mod. Phys., July 1948; v. 20, pp. 457-472.

The term electret was coined by Oliver Heaviside to denote a permanently electrified substance exhibiting electrical charges of opposite sign at its extremities. This article describes its nature and behavior, and reviews earlier investigations.

ELECTRIC HEATING

Heating with Electricity, by Carl F. Boester.
Heat. Piping & Air Cond., July 1948; v. 20, pp. 92-94.

Short article on the use of electricity for space heating by the radiant and the heat-pump methods.

FOUNDRY PRACTICE

Permanent Mold Casting of Copper-base Alloys, by James L. Erickson.
Iron Age, July 22, 1948; v. 162, pp. 84-89.

A comprehensive review of current British practice in casting copper-base alloys in permanent molds, with particular emphasis on mold material and mold coatings.

GEARS

Backlash Considerations When Designing Gears, by Louis D. Martin.
Prod. Engng., July 1948; v. 19, pp. 108-112.

Cost of backlash and methods for determining amount needed and amount obtained. Designs that produce zero backlash in gears for specific installations.

HARDNESS—TESTING

Methods and Instruments for Hardness Testing, by A. M. White.
Steel, July 26, 1948; v. 123, pp. 74-76, 78, 80, 82.

A discussion of the development of hardness testers based on scratch, rebound, penetration, magnetic and electrical principles, and descriptions of common testers in use today.

JET PROPULSION

P-80 Still "Right" After Five Years, by Robert McLarren.
Aviation Week, July 19, 1948; v. 49, pp. 22, 25-26.

An account of the development and status of the Lockheed P-80 jet-propelled airplane.

LUBRICATION AND LUBRICANTS

Some Vibration Aspects of Lubrication, by A. C. Hagg.
Lubrication Engng., Aug. 1948; v. 4, pp. 166-169.

The role of bearings in forced and self-excited vibration of machines is described. The important influence of oil-film damping in limiting vibration amplitude at resonance is shown by a practical example.

MAGNETIC PROPERTIES—TESTING

Cathode-ray Magnetization Curve Tracer, by M. V. Scherb.
Rev. of Sci. Instr., July 1948; v. 19, pp. 411-419.

An instrument developed to measure the magnetic properties of materials in a variety of forms by oscillographic techniques.

PLASTICS

Plastics as Paper Coatings, by William H. Aiken.
Modern Packaging, July 1948; v. 21, pp. 193-197.

A summary of characteristics desired in coatings and an examination of the properties of each of the available materials.

RADIO ENGINEERING

Precision Double-pulse Generator, by D. L. Medley and H. D. Rathgeber.
Jour. Sci. Instr., July 1948; v. 25, pp. 234-236.

For producing either single or repeated pairs of electrical pulses, similar to Geiger-counter discharges, separated by a time interval that is continuously adjustable.

REFRIGERATING ENGINEERING

Application and Characteristics of Capillary Tubes, by H. F. Lathrop.
Refrig. Engng., Aug. 1948; v. 56, pp. 129-133.

The application and performance of capillary tubes as used in the control of refrigerants.

SHIP PROPULSION

Single-screw Oil-tank Motorship *Auris*.
Shipbldr. & Mar. Engine-Bldr., July 1948; v. 55, pp. 448-452.

Description of a notable diesel-electric a-c installation.

SOUND

Calculation of the Directivity Index for Various Types of Radiators, by C. T. Molloy.
Acoustical Soc. of Am. Jour., July 1948; v. 20, pp. 387-405.

Gives the derivations of the "directivity index" formulas for several types of sound radiators.

STANDARDS—RADIOACTIVITY

Measurement of Radioactive Isotopes.
Nucleonics, Sept. 1948; v. 3, pp. 55-59.

Recognizing the need for radioisotope comparison standards for precision measurements, the Bureau of Standards has developed such standards. Their preparation and use are here outlined.

TELEVISION—TRANSCRIPTION

Television Recording Camera, by J. L. Boon and others.
Soc. Motion Pict. Engrs. Jour., Aug. 1948; v. 51, pp. 117-126.

A 16-mm motion-picture camera for recording television programs at sound speed from a monitor receiving tube is described.

WAVE GUIDES

Radiation Patterns of Dielectric Rods—Experiment and Theory, by R. B. Watson and C. W. Horton.
Jour. App. Physics, July 1948; v. 19, pp. 661-670.

A theory is developed describing the electromagnetic radiation from dielectric rods used as terminations to rectangular wave guides.

WELDS—TESTING

Research on Arc-welded Butt Joints of Mild Steel, by Georges Welter.
Weld. Jour., July 1948; v. 27, pp. 321s-369s.

Investigation on ductility, impact tensile resistance, effect of notching, cyclic loads, axial and eccentric loads, carried out in room and sub-zero temperatures.

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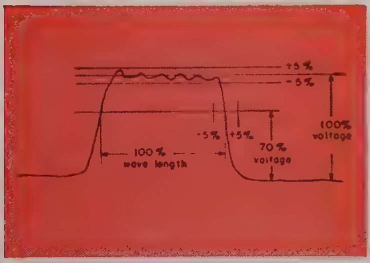

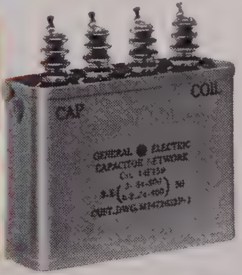

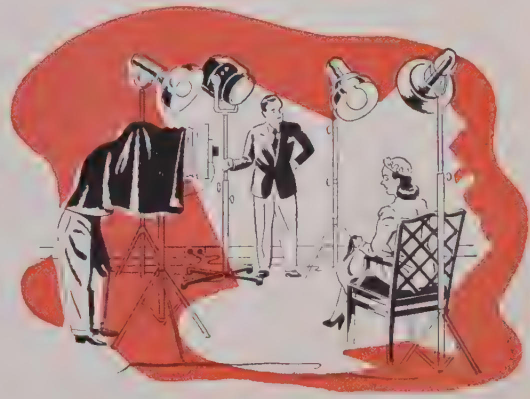

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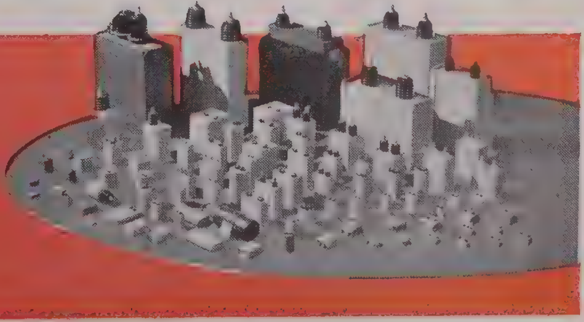

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GENERAL ELECTRIC Review

DECEMBER, 1948
Vol. 51, No. 12

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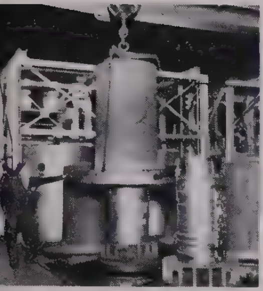

THE COVER

Typical of numerous similar installations: a bell-ype electric furnace, bright-annealing high-carbon oiled steel strip in one of America's prominent teel mills. Uniform annealing of the strip, due to even distribution of the heat throughout the charge during annealing cycles, and good operating economy give high quality at low cost. Brightness of the strip is assured by use of protective atmos-pheres surrounding the charges within sheet-alloy etorts during the heating and cooling cycles.

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CIRCULATION DEPARTMENT: General Electric Review, Schenectady 5, New York.

SUBSCRIPTION RATES: *Payable in advance.* United States and Possessions and countries in Pan-American Union, one year $3.50, two years $5.50. Canada, one year $3.75, two years $5.75. Other foreign countries, $4.00 a year, $6.00 two years. Public and college libraries, professors, and enrolled students deduct $1.00 from annual rates. SINGLE COPY 35¢

CHANGE OF ADDRESS: Give old and new addresses. Notices received before the fifteenth of the month will be effective with the next issue.

ADVERTISING DEPARTMENT: General Electric Review, Schenectady 5, New York.

Entered as second-class matter, March 26, 1912, at the post office at Schenectady, N. Y., under Act of March 3, 1879. Published monthly by General Electric Company, 1 River Road, Schenectady 5, N. Y. Printed in U. S. A.

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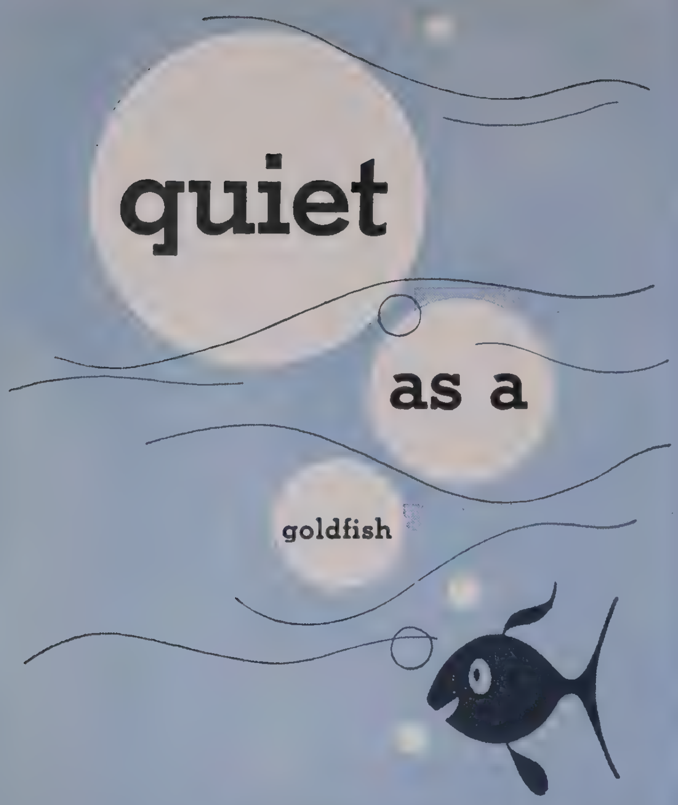

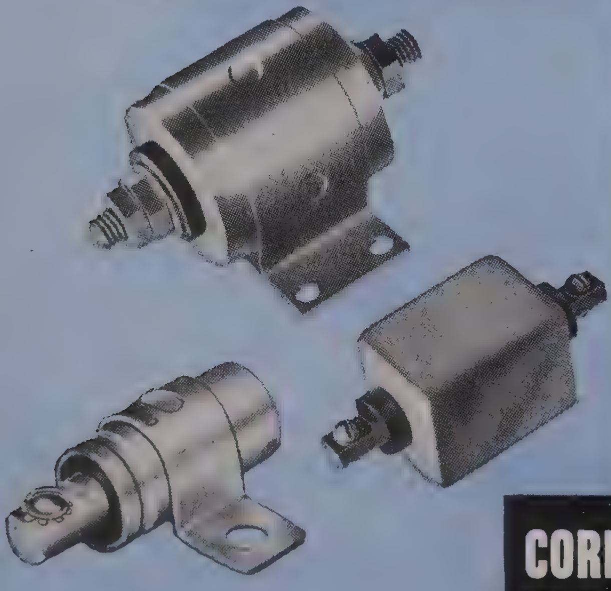

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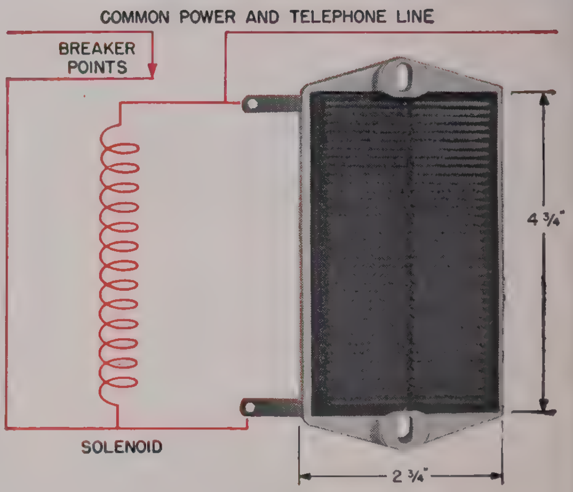

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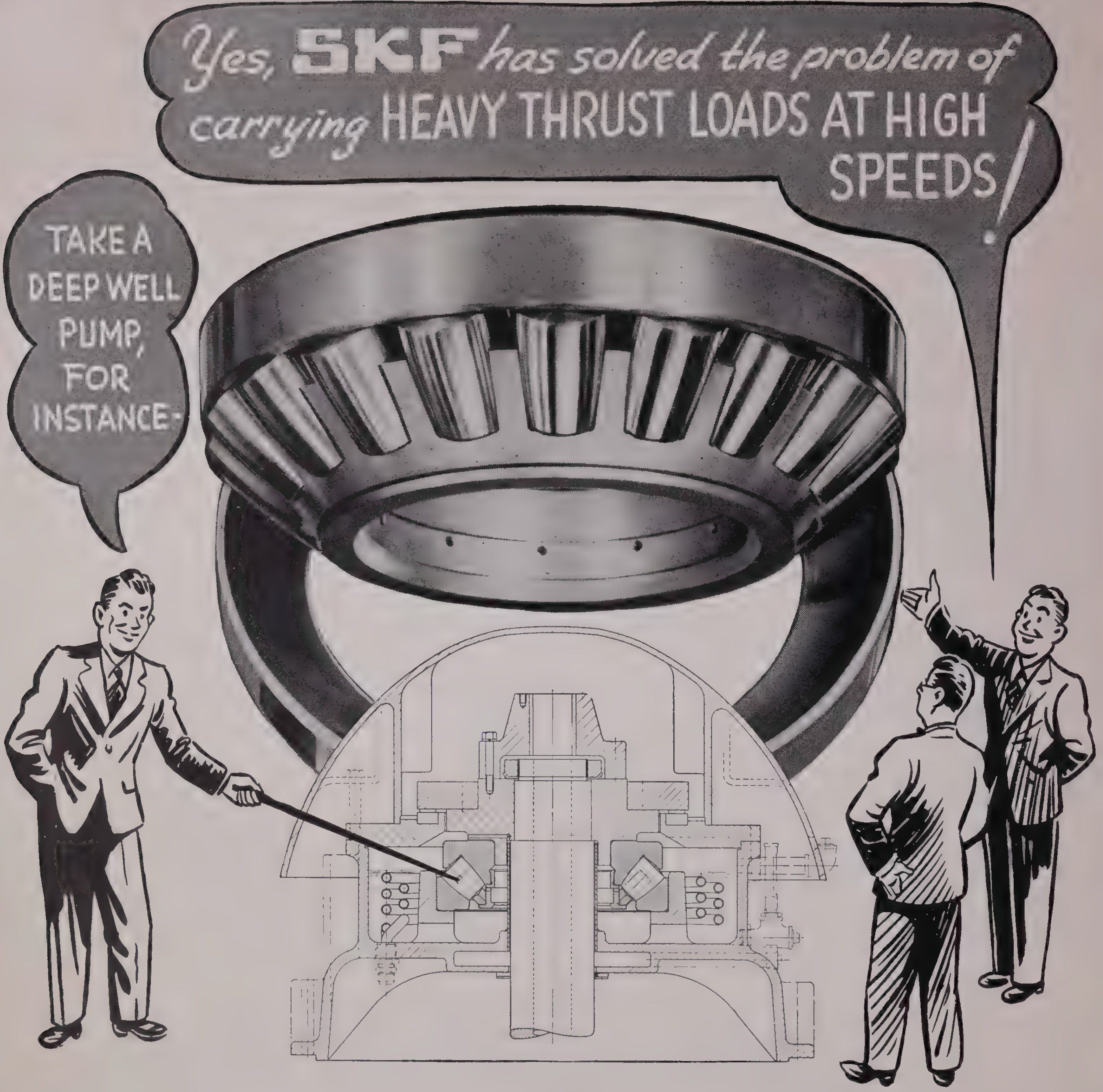
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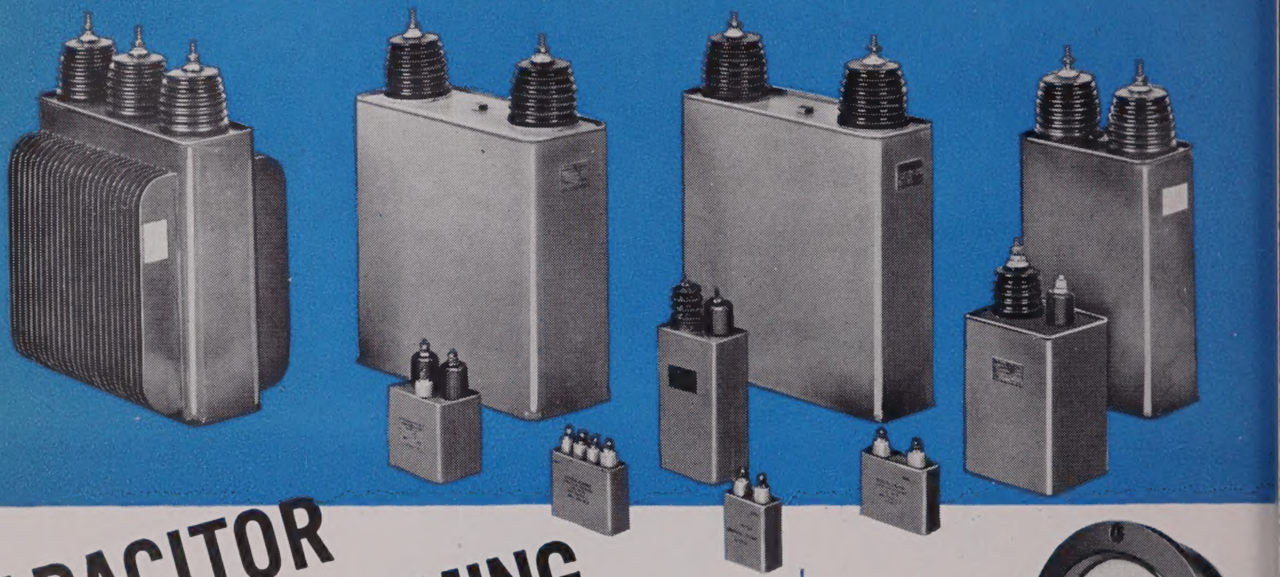

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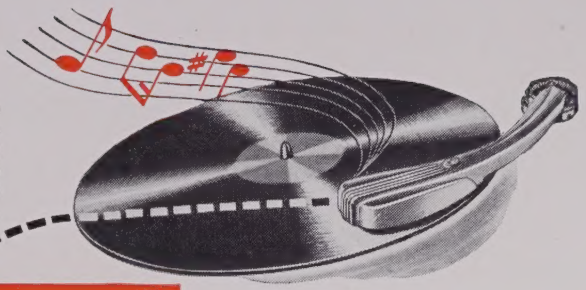

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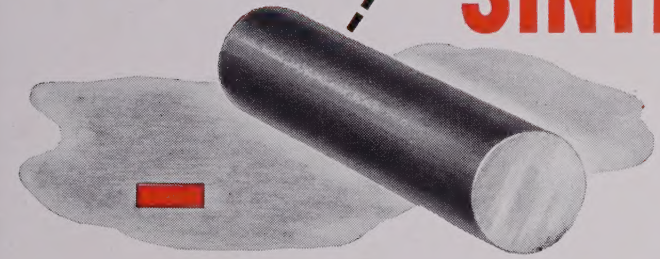

Actual size of G-E SINTERED ALNICO 5 permanent magnet used in the G-E Electronic Reproducer is shown in red.

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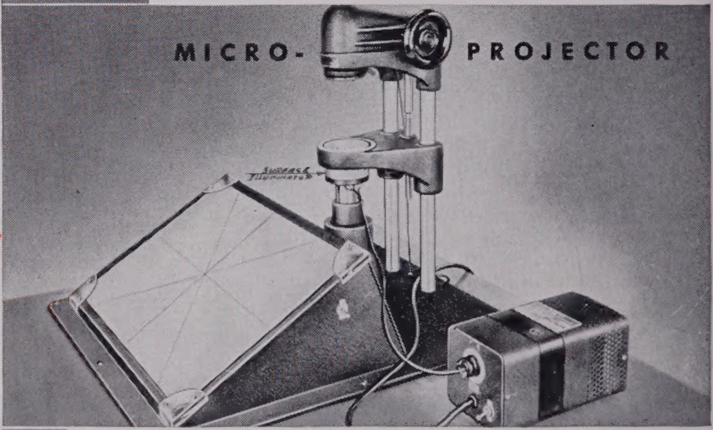

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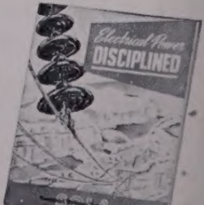

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